Economic Geology of the Platinum Metals

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Economic Geology of the Platinum Metals

By JOHN B. MERTIE, Jr.

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A summary report on the geology of the platinum deposits of the world, with a discussion of the chemistry and mineralogy of the platinum group of metals and a comprehensive bibliography

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ABSTRACT

Platinum was discovered first in Colombia, but the exact date is unknown, though it was described as early as 1557. Mining of the platinum placers of Colombia began in 1778, and until 1823 this state was the only source of the platinum metals. Rich platinum placers were discovered in the Ural Mountains, between Russia and Siberia, in 1822, and within a few years Russia became and remained for many years the world's greatest producer. Placer platinum was mined in Canada as early as 1885, but it was not until 1919 that the platinum metals began to be recovered from the nickel-copper lodes of the Sudbury district. By 1936, Canada had become a producer of first rank. Platinum was found in the Transvaal, Republic of South Africa, in 1923, and the deposits of the Bushveld complex were discovered in the following year. In 1956 and 1957 the output of these lodes outstripped the Canadian production, though in later years the South African production was deliberately reduced for economic reasons. Russia for a long time ranked third, but as the Uralian placers became depleted, lodes were found in Siberia that by 1961 raised the Russian output to first rank. Platinum placers were discovered in Alaska in 1929, and since 1934 this State has ranked fifth in world production, with Colombia fourth. The Witwatersrand district, of South Africa, ranks sixth, but nevertheless is the world's greatest producer of osmiridium (iridosmine).

Placer deposits of the platinum metals occur throughout the world, and up to the end of the first quarter of the 20th century constituted all the world's supply. The discovery of the platiniferous lodes of Canada and South Africa, and later those of Siberia, completely altered this situation. As of 1965, the three largest producing countries were the Union of Soviet Socialist Republics, the Republic of South Africa, and Canada, which together produce more than 98 percent of the world's output; Colombia and the United States together contribute 1½ percent, and a few other nations add the remainder. Judging by the exploration already done, the Republic of South Africa appears to have the largest reserves.

The six platinum metals occur commonly in placers as two intergrown alloys, of which one has a high tenor in platinum, a much lower tenor in iridium, and small tenors in the other four elements. The second alloy consists mainly of iridium and osmium, with considerable ruthenium, less rhodium and platinum, and an exceedingly small amount of palladium, if any.

The platinum metals that occur in bedrock lodes exist mainly as platinum minerals, wherein the platinum elements, gold, silver, and certain base metals function as cations in combination generally with arsenic, antimony, bismuth, sulfur, tellurium, oxygen, and other anions. Small amounts of native alloys are also present in some bedrock ores, notably in those of the Transvaal, Republic of South Africa.

A genetic classification of the platinum lodes and placers constitutes a part of this report. In the discussion of lodes, six types of host rocks or environments are enumerated. The two major lode systems are exemplified by the basic rocks of the Sudbury district, Ontario, Canada, and by the basic and ultrabasic rocks of the Transvaal, Republic of South Africa, both of which occur in elongate elliptical basins which have been designated as lopoliths. This similarity has suggested a genetic uniformity in the origin of the intrusive rocks and of the related nickel-copper-platinum lodes at these two sites, but this is fallacious. The intrusive rocks of Sudbury include few if any ultrabasic rocks; they have not been proven to have originated by magmatic or gravitative differentiation, and the platiniferous lodes occur mainly, not within the intrusives, but either along the margins of the intrusive rocks, or as offset deposits at considerable distances from them. The igneous rocks of the Bushveld complex, in the Transvaal, include basic and many types of ultrabasic rocks; they are generally admitted to have resulted from magmatic differentiation, and the principal platinum horizon, the Merensky reef, occurs in ultrabasic rocks far from the bounding sedimentary rocks.

A third type of lode comprises those deposits of the platinum metals which occur in peridotites and perknites, commonly in dunite and serpentinite, less commonly in pyroxenic rocks containing little or no olivine. The distinctive feature of these lodes is that the platinum metals occur as native alloys, which are either concentrated in lenticular masses of chromite, or are sparsely and widely distributed in association with chromite, within the ultrabasic rocks. Such deposits have yielded no major lodes of economic value though some small ore bodies of this kind have proven to be of phenomenally high grade. By prolonged erosion and alluvial concentration, however, the platinum metals of these deposits have been concentrated to produce stream and beach placers, mainly the former. Lodes of this type have been the sources of the placers of the Russian Urals, Colombia, Alaska, and so far as known, of all the other platinum placers of the world. The three other types of ores, mentioned in a later section (p. 17), have little significance, either as lodes or sources of placers, though a few of them have been mined, generally with little or no profit.

The genetic classification of the platinum placers is similar to what the writer has elsewhere used for gold placers. Seven types of placers are listed, including the lithified placers exemplified by the gold-osmiridium deposits of the Witwatersrand, Republic of South Africa. Most of the alluvial deposits

described in this report are either ancient or recent stream placers.

The physical and chemical properties of the platinum metals are stated in the following pages, and their mineralogy is fully discussed. Two tabulations are presented that attempt to separate the alloys from the chemical compounds, or true minerals. A large number of analyses of the platinum metals, mainly of the natural alloys, are given; whereas the analytical data on the platinum metals recovered from lodes are based mainly on the records of production. But even the analyses of the native metals are composite, in that they are based commonly upon bulk samples of two alloys. Chemical analyses are rated by the writer as superior or inferior according to whether or not they state the percentages of all the platinum metals of the samples. Several firms in the United States are able to make superior analyses, but outside the analyses made by Johnson, Matthey and Co. for the Goodnews Bay Mining Co., Alaska, very few superior analyses are obtainable.

This report is devoted mainly to a description of the more important platinum deposits of the world, of which three are productive on a major scale and three on a minor scale. Other deposits that were formerly mined, some that now produce small amounts of the platinum metals, and other that have geologic rather than economic significance are also described. If the data are available, the topics discussed are the discovery, mining and production, general geology, character and genesis of the deposits, and the composition of the platinum metals. Canadian, South African, Russian, and Colombian deposits are rather fully discussed; in lesser detail are also described the sources of the platinum metals in Australia, New Zealand, Japan, Ethiopia, Sierra Leone, New Guinea, Borneo, Sumatra, and other countries. The deposits of Alaska are described in considerable detail, partly because they are of national importance and partly because many cogent data on them are available.

Two bibliographies are presented, one of foreign occurrences of the platinum metals and one of domestic occurrences. Papers relating to some of our domestic deposits are shown in both bibliographies.

INTRODUCTION

The earliest recorded use of platinum, according to Farabee (1921, p. 43–52), was by the Indians of Ecuador, who made artifacts of platinum bonded by gold, before the discovery of America by Europeans. Probably the first allusion to platinum was made by the Italian Julius C. Scaliger (1557) in his book entitled "On Subtlety" (in Latin). The Spaniard, Antonio de Ulloa (1748, p. 606), in describing his travels in South America, mentioned the occurrence of "platina" in the Chocó district. The first investigative work was done by Charles Wood, an English metallurgist and assayer, who acquired some platinum in Jamaica in 1748 that had come from Cartagena (Colombia), and he sent a part of it to a relative, Dr. William Brownrigg, in London. Dr. Brownrigg investigated the properties of the new metal, and in 1750 presented samples to the Royal Society of London. Shortly thereafter, Sir William Watson (1750, p. 671–676) and Dr. Brownrigg contributed to the Philosophical Transactions a careful description of platinum. Later and more detailed studies of platinum residues led to the discovery of palladium and rhodium by William H. Wollaston (1805), and of iridium and osmium by Smithson Tennant (1805). Ruthenium was separated in impure form by G. W. Osann (1827), and was later purified and described by Karl K. Klaus (Carl E. Claus) (1845, 1847). These and many additional details of the discovery of the platinum metals are admirably presented by Weeks and Leicester (1968). A complete history of the platinum metals, from the time when platinum was discovered until 1890, has been written by Donald McDonald (1960b) and published by Johnson, Matthey and Co., of London. This company also publishes a quarterly journal entitled the "Platinum Metals Review," of which the first issue appeared in January 1957. The most important treatise on the platinum metals of recent date is by Heinrich Quiring (1962, 288 p.)

Mining of the platinum placers of Colombia began in 1778, and these deposits remained the only source of the platinum metals until the Russian deposits were discovered. Platinum was found first in the gold placers of the Ural Mountains in 1822, but rich platinum placers were discovered in 1824, which made Russia the world's largest producer, with Colombia second. The declining production from the Russian placers has in recent years been compensated in large measure by the recovery of platinum metals as a byproduct in mining the nickel-copper ores of the Noril'sk district, northwestern Siberia, and other lodes.

Platinum was recognized in Canada in 1852, and platinum placers were mined as early as 1887. Platinum was discovered in the Sudbury district, Canada, in 1885, but it was not until 1919 that production from the nickel-copper mines of that district began on a large scale. By 1936, Canada had become a producer of first rank.

Osmiridium was first found in South Africa in 1892, and the first recorded discovery of platinum in the central Transvaal was in 1923. Commercial production of platinum metals from the nickel-copper ores of the Bushveld igneous complex began in 1925, and in 1956 and 1957 the Republic of South Africa was the largest producer of the platinum metals. In subsequent years, however, this output was purposely curtailed, to meet the demands of the metal markets. Osmiridium (iridosmine) began to be produced commercially in 1921, and in recent years the output has remained relatively constant, as this alloy is a byproduct of gold mining in the Witwatersrand. This production, though small, is the world's principal source of osmiridium, which

formerly was produced by Russia, Tasmania, Japan, and Papua.

The uses to which the platinum metals are put vary from year to year, as new industrial applications are devised. The latest data, as given for 1965 by the U.S. Bureau of Mines, are shown in table 1.

The chemical and electrical industries utilize nearly three-quarters of the platinum metals produced by and imported into the United States. Especially noteworthy is the large amount of palladium used by the electrical industry, and it may be noted that 350,000 ounces of palladium was used by the telephone companies in 1964 for contacts, mainly in relays. Both palladium and platinum are used by the oil industry as catalysts, but the lower cost of palladium gives it preference over platinum, where the substitution is possible. Only about 5 percent of the total available palladium is used for jewelry; because it is lighter than platinum it is used for brooches and large ornaments where it is desirable to reduce weight. The illegally produced and refined platinum (see section on "Colombia") is unsatisfactory for purposes where specified alloys are required, such as catalysts, and this accounts for its diversion into the jewelry trade. It is significant that, owing to the high resistance of the platinum metals to chemical corrosion, most of the uses are nondestructive, so that an increasing volume of secondary platinum metals is being recovered.

TABLE 1.—*Uses, in ounces, of the platinum metals in the United States, 1965*

[Source: U.S. Bur. Mines]

Application	Pt	Ir	Os	Ru	Rh	Pd	Total	Percent
Chemical	131, 599	3, 006	1, 479	3, 103	12, 499	156, 796	308, 482	26
Electrical	106, 808	3, 483	10	2, 647	7, 924	430, 384	551, 256	46
Petroleum	81, 200	6	75		369	37, 001	118, 651	10
Dental and medicinal	26, 511	294	32	142	124	50, 192	77, 295	7
Jewelry and decorative	35, 387	2, 639		860	7, 498	18, 203	64, 587	5
Glass	19, 846	8			10, 275	1, 402	31, 531	3
Miscellaneous	10, 084	118	38	1, 331	221	23, 107	34, 899	3
Total	411, 435	9, 554	1, 634	8, 083	38, 910	717, 085	1, 186, 701	100

One of the interesting national uses to which platinum was formerly put was the coinage by Russia of 3-, 6-, and 12-ruble coins, which began in 1828 and continued until 1846. These three coins had weights respectively of 0.333, 0.666, and 1.332 troy ounces, or approximately 10.358, 20.715, and 41.431 grams; and their diameters were approximately 23, 28, and 36 millimeters. Thus the 3-ruble coin was comparable in size with a U.S. quarter dollar, which has a diameter of about 24 millimeters. According to McDonald (1960b, p. 165), quoting Deville and Debray, the composition of the Russian ruble coins, recomputed to total 100 percent, was as follows:

Composition of Russian platinum coins

	Percent		Percent
Platinum	96. 13	Palladium	0. 25
Iridium	1. 19	Iron	1. 54
Rhodium	. 49	Copper	. 40
		Total	100. 00

It also is stated by McDonald that 1,373,691 coins of 3 rubles, 14,847 coins of 6 rubles, and 3,474 coins of 12 rubles were minted, with a total content of 485,505 troy ounces of platinum. Any of these are now considered rare items by coin dealers in the United States.

The platinum metals have different values, depending mainly upon their desirability for different uses, and their natural plenitude or scarcity. The market price of ruthenium remained constant during 1966 and the first 4 months of 1967, but the prices of the other five metals increased steadily during the same period, according to the following tabulation:

Market prices of platinum metals in 1966 and part of 1967

[Dollars per troy ounce]

Platinum	\$100, January 1–December 31, 1966
	\$109–\$112, February 1–April 30, 1967
Iridium	\$100–\$115, January 1–February 28, 1966
	\$125–\$130, March 1–April 19, 1966
	\$140–\$145, April 20–June 19, 1966
	\$170, June 20–December 31, 1966
	\$185–\$190, January 1–April 30, 1967
Osmium	\$300–\$350, January 1–October 2, 1966
	\$300–\$450, October 3, 1966–April 30, 1967
Ruthenium	\$55–\$60, January 1, 1966–April 30, 1967
Rhodium	\$182–\$185, January 1–February 28, 1966
	\$195–\$200, March 1–December 31, 1966
	\$210–\$225, January 1–April 30, 1967
Palladium	\$32–\$34, January 1–June 9, 1966
	\$33–\$35, June 10–October 2, 1966
	\$35–\$37, October 3–December 31, 1966
	\$37–\$39, January 1, 1967–April 30, 1967

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WORLD PRODUCTION

The Union of Soviet Socialist Republics, the Republic of South Africa (exclusive of the Witwatersrand), and Canada had productions in 1965 respectively of 1,700,000, 750,000, and 463,000 troy ounces, derived mainly from lodes, though in part (Russia) from placers. Canada was the largest producer of platinum metals (exclusive of osmiridium) from 1936 to 1955 and from 1958 to 1960. The Republic of South Africa was the largest producer in 1956 and 1957, but a collapse in the metal markets in 1958 resulted in a temporary curtailment of the South African output. In the "Platinum Metals Review," of 1966 and 1967, however, the Rustenburg Platinum Mines, Ltd., principal South African producer, announced a marked expansion in mining activities that will result in a production of 850,000 ounces by 1969.

Lack of exact information renders it difficult to appraise correctly the Russian output, as the U.S.S.R. does not make public its production of many mineral products, particularly those of strategic value. Up to 1953, the production of the U.S.S.R. was estimated nominally by the U.S. Bureau of Mines at 100,000 ounces, but the volume of platinum metals[1] imported by the United States from Russia during the Second World War was so great as to indicate either that the nominal estimate of an annual production of 100,000 ounces was a gross underestimate, or that the platinum metals had been stockpiled in Russia over a considerable number of years. Therefore, beginning in 1954, the Russian output was estimated by the U.S. Bureau of Mines at 200,000 ounces, and this figure has been increased gradually to a maximum of 1,700,000 ounces for 1965. Thus, in 1961, the Union of Soviet Socialist Republics became, and has remained, the principal producer of the platinum metals.

Regardless, however, of comparative outputs the reserves and therefore the potential production of the Republic of South Africa appear to be much greater than those of any other country. One marked difference between the South African lodes and those of Canada and the U.S.S.R. is that platinum metals are the principal output of the former, with a byproduct of nickel, copper, and other metals, whereas in the two latter countries the reverse is true.

Colombia, the United States, and the Witwatersrand, of the Transvaal and Orange Free State, had annual productions, respectively, for 1965 of 11,040, 40,487, and 6,000 troy ounces, but these outputs require some explanation. The production of Colombia is obtained from placers which are mined by dredging, but in addition, thousands of natives are also engaged in mining on a very small scale. The individual outputs of these people are small, but in the aggregate their production considerably exceeds that of the dredges. Most of this individually mined gold and platinum is purchased by speculators who smuggle it out of the country, and therefore such platinum is not officially recorded. Hence, the production stated by the Colombian government, and accepted by the U.S. Bureau of Mines, may probably be doubled. Parenthetically, much of this smuggled and illegally processed platinum is not carefully and completely refined, but this does not detract from its use in jewelry. Hence, a large part of it is channeled into the jewelry business.

The output given for the United States includes the platinum metals produced in placer mining, together with those that are recovered as a byproduct of the mining of gold and copper lodes. In addition, there is an important increment that results from the salvage of industrial wastes and from jewelry and dental products that were saved and reworked. The Goodnews Bay Mining Co. is the only concern in the United States that is engaged primarily in mining the platinum metals, though a very small output is also obtained as a byproduct of gold dredging in California. Therefore the Goodnews production may not be specifically cited, but instead is included with the other primary sources above cited. The production from Goodnews Bay, however, is less than that given for Colombia.

Certain districts in North America, Asia, Africa, and Oceania that formerly had outputs in excess of 1,000 ounces are now either very small producers or nonproducers. Present or past minor sources are in the following countries or parts thereof:

Lodes

1. Katanga (Republic of the Congo). A byproduct of the copper lodes, recovered in the refineries.

Placers

2. British Columbia.
3. California, Oregon, and other Western States.
4. Australia, including Tasmania, New South Wales, Victoria, and Queensland.
5. Ethiopia.
6. Sierra Leone.
7. Papua, Territory of New Guinea, and Netherlands New Guinea.
8. Borneo and Sumatra.
9. Japan.
10. Several other countries with present or former outputs of very small size.

[1] Data acquired from the War Production Board, 1945.

Panama is not included in the list of minor producers, though it was credited with an output of 267 ounces in 1937. No significant production, however, is recorded before or after that date, and it is probable that a part of the output of 1937 was platinum that was smuggled out of Colombia.

The world's total production of platinum metals has not been accurately recorded, but it believed, as of 1965, to be about 42,500,000 troy ounces, and the annual production in the United States constitutes only 1.2 percent of the world's annual production.

The statistics of the world's production of platinum metals for the period 1882–1966 are given in the "Mineral Resources" volumes (1882–1923) of the U.S. Geological Survey and in the "Minerals Yearbooks" (1924–66) of the U.S. Bureau of Mines. A valuable compilation of world production, classified by countries and by platinum alloys, has recently been published by Quiring (1962, p. 93–101). The world's production of platinum metals by countries from 1951 to 1966 will suffice as a necessary background for the contents of this report. These data are presented in table 2.

Canada produces about equal amounts of platinum and palladium; about 72 percent of the output of the Republic of South Africa is platinum, but 70 percent of the Russian production is palladium. As Russia has the largest output, it follows that more palladium is produced in the world than platinum. The output ratio of palladium to platinum is about 3:2.

PLATINUM METALS

PHYSICAL PROPERTIES

The platinum group of metals comprises platinum, iridium, osmium, ruthenium, rhodium, and palladium. Platinum, iridium, and osmium have the greatest density, and iridium is now recognized as the heaviest element that occurs in nature. Ruthenium, rhodium, and palladium have densities that average only 55 percent as great. Thus these six elements are divided by their densities into two sets, which are analogous to gold and silver, and just as native gold is invariably alloyed with silver, so all six of these elements are invariably present as native alloys of the platinum metals.

The platinum metals may be tabulated in different ways, but the listing used in this exposition begins with platinum and ends with palladium, as they are the most plentiful of these elements, and in a circular arrangement would adjoin one another. Platinum, iridium, and osmium are arranged in their order of decreasing atomic number and atomic weight and increasing melting point, boiling point, and hardness. Ruthenium follows osmium, because these two hexagonal elements should be together. Rhodium occupies the remaining fifth place in the tabulation. The principal properties of the platinum metals are shown in tables 3–5. In the compilation of these data, a number of sources were consulted, and the most reasonable and consistent were accepted. Among the sources utilized were Bishop and Co. (1931), Vines and Wise (1941), Gilchrist (1943), Zvyagintsev (1946), Selwood (1956), Way and others (1950), Wise (1953), Wise and Gilchrist (1949), Engelhard Industries, Inc. (1965), and Johnson, Matthey and Co., Ltd. (1963).

The platinum metals, as shown in table 3, are paramagnetic, as opposed to gold and silver, which are diamagnetic. Palladium has the greatest and osmium the smallest magnetic susceptibility. Palladium has a higher magnetic susceptibility than any other nonferromagnetic element so far determined. The magnetic susceptibility and other physical properties of the natural alloys of the platinum metals cannot be predicted by linear interpolation based upon the known proportions of their elements, and in fact, unexpectable properties may exist in such alloys or compounds. Thus, certain natural alloys of the platinum elements are ferromagnetic though none of the pure metals are ferromagnetic. This has frequently been explained by the presence of a high content of iron in the dross, coupled perhaps with a high tenor of palladium, but such assumptions are not necessarily valid, as pyrite (FeS_2) has a high content of iron, but is not ferromagnetic. Ordinary hematite (Fe_2O_3) is likewise paramagnetic, though maghemite (γ–Fe_2O_3) is ferromagnetic. On the other hand, the Heusler alloys, containing commonly the paramagnetic elements manganese, aluminum, and copper, are strongly ferromagnetic, with a Curie point at 330°C. Also, a weakly ferromagnetic element, in combination with some paramagnetic element, may yield a highly ferromagnetic alloy. Thus, Pertinax II, as described by Darling (1963, p. 96–103) and Ford (1964, p. 82–92), which contains 76.7 percent platinum and 23.3 percent cobalt, is the most powerful permanent magnet so far developed. And finally, two diamagnetic elements may be combined to produce a ferromagnetic compound. An example is silver difluoride (AgF_2), with a Curie point at −110°C.

The natural alloys of the platinum metals are handled differently by producers than the natural alloys of gold and silver that constitute placer gold

TABLE 2.—*World production of platinum metals, in troy ounces, 1950–66*

[Compiled from U.S. Bureau of Mines Yearbooks, 1950-66]

	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966
North America:																	
Canada:																	
Lodes and placers	273,312	318,268	279,724	302,563	343,706	384,746	314,808	416,147	300,458	328,096	453,604	418,278	470,787	357,651	376,238	463,127	385,741
United States:																	
Placers, and discoveries from refineries	37,858	36,951	34,409	26,073	24,235	23,170	21,398	18,531	14,359	15,485	23,609	43,248	28,742	49,750	40,487	35,026	
South America:																	
Colombia:																	
Placers	26,445	32,000	33,700	29,201	28,465	40,674	32,947	24,267	19,619	31,498	28,855	20,160	14,100	22,983	20,647	11,040	
Europe:																	
U.S.S.R.:																	
Lodes and placers	100,000	100,000	100,000	100,000	200,000	250,000	250,000	250,000	250,000	300,000	330,000	500,000	800,000	800,000	1,500,000	1,700,000	
Asia:																	
Japan:																	
Refineries (Pt plus Pd)	210	268	569	1,058	1,595	858	716	3,802	1,323	811	1,959	3,797	3,244	3,040	4,074	4,074	
Philippines:																	
Refineries (Pt plus Pd)												392	313				
Africa:																	
Republic of South Africa:																	
Lodes	144,217	190,898	232,521	290,177	338,162	381,732	484,574	603,704	300,000	375,000	400,000	350,000	300,000	300,000	600,000	750,000	
Lithified placers	6,914	6,359	6,141	6,966	6,266	7,021	6,696	5,361	4,873	5,352	6,334	7,000	6,000	5,500	6,000	6,000	
Republic of the Congo:																	
Lodes, Katanga (Pt plus Pd)					176		160	325	161					7	5		
Ethiopia:																	
Placers	641	266	100	366	230	251	244	248	180	68	189	180	180	180	180	353	
Sierra Leone:																	
Placers								5	8								
Oceania:																	
Australia:																	
Placers (Pt plus Pd)	64	41	51	59	30	28	44	53	64	3	4	2	2	4		122	
New Guinea:																	
Placers		7	7	6	9	10	9	14	28	16	4	2	5	5	2	4	
New Zealand:																	
Placers		8	4	2	1												
Total	589,658	695,186	687,236	760,670	942,884	1,088,490	1,111,596	1,322,487	891,075	1,056,330	1,274,558	1,343,059	1,623,373	1,539,120	2,547,633	2,909,746	

Table 3.—*Physical properties of the platinum metals, gold, and silver*

Precious metals	Atomic number	Atomic weight	Density at 20° C	Hardness (Moh's scale)	Melting point (° C)	Boiling point (° C)	Common valence numbers	Workability
Platinum	78	195. 2	21. 45	4. 3	1, 769	3, 800	2, 4	Malleable and ductile.
Iridium	77	193. 1	22. 65	6. 5	2, 443	4, 500	3, 4	Brittle.
Osmium	76	190. 2	22. 61	7. 0	3, 045	5, 020	4, 6, 8	Do.
Ruthenium	44	101. 7	12. 45	6. 5	2, 310	4, 080	3, 4, 6, 8	Brittle, cold. Malleable, red heat.
Rhodium	45	102. 9	12. 41	6. 0	1, 960	3, 700	3	Do.
Palladium	46	106. 7	12. 02	4. 8	1, 552	2, 900	2, 4	Malleable and ductile, but less so than platinum.
Gold	79	197. 2	19. 27	2. 5	1, 063	2, 808	1, 3	Very malleable and ductile.
Silver	47	107. 9	10. 50	2. 7	961	2, 210	1, 2, 3	Malleable and ductile, but less so than gold.

	Electrical resistivity (microhms/cm³ at 0° C)	Specific heat (cal/g/° C at 0° C)	Thermal conductivity, 0°-100° C (cal/cm/cm²/sec/° C)	Thermal expansivity, 20°-100° C (micro-cms/cm)	Young's modulus, E (kg/mm²/×10⁻³)	Shear modulus, G (kg/mm²/×10⁻³)	Bulk modulus, K (kg/mm²/×10⁻³)	Index of ductility, $\frac{K}{G}$	Atomic magnetic susceptibility, χ_A (cm³/g/×10⁶)
Platinum	9. 85	0. 0314	0. 17	9. 1	17. 40	6. 22	28. 09	4. 52	+189. 6
Iridium	4. 71	. 0307	. 35	6. 8	53. 83	21. 40	37. 80	1. 77	+25. 7
Osmium	8. 12	. 0309	. 21	6. 1	56. 00	22. 00	38. 00	1. 73	+9. 9
Ruthenium	6. 71	. 0551	. 25	9. 1	43. 00	17. 20	29. 20	1. 70	+43. 4
Rhodium	4. 33	. 0589	. 36	8. 3	38. 64	15. 30	28. 01	1. 83	+101. 9
Palladium	9. 93	. 0584	. 18	11. 6	12. 83	46. 10	19. 09	4. 14	+558. 1
Gold	2. 06	. 0308	. 74	14. 2	8. 02	2. 82	17. 46	6. 19	−29. 6
Silver	1. 59	. 0559	1. 01	19. 7	8. 05	2. 94	10. 18	3. 46	−22. 7

Table 4.—*Crystalline structure and electronic configuration of the platinum metals, gold and silver*

Metal	Crystalline structure	Space group	Electronic configuration														Atomic radius in angstroms (cm×10⁻⁸)
			K	L		M			N				O			P	
			s	s	p	s	p	d	s	p	d	f	s	p	d	s	
Platinum	Cubic, Fcc	Fm 3 m	2	2	6	2	6	10	2	6	10	14	2	6	9	1	1. 38
Iridium	Cubic, Fcc	Fm 3 m	2	2	6	2	6	10	2	6	10	14	2	6	7	2	1. 35
Osmium	Hexagonal, Cph	C6/mmc	2	2	6	2	6	10	2	6	10	14	2	6	6	2	1. 32
Ruthenium	Hexagonal, Cph	C6/mmc	2	2	6	2	6	10	2	6	7		1				1. 31
Rhodium	Cubic, Fcc	Fm 3 m	2	2	6	2	6	10	2	6	8		1				1. 34
Palladium	Cubic, Fcc	Fm 3 m	2	2	6	2	6	10	2	6	10						1. 37
Gold	Cubic, Fcc	Fm 3 m	2	2	6	2	6	10	2	6	10	14	2	6	10	1	1. 42
Silver	Cubic, Fcc	Fm 3 m	2	2	6	2	6	10	2	6	9		2				1. 44

Native gold is diamagnetic, so that most of the black sand that is not removed by washing may be separated magnetically. After sieving to remove the coarser lead shot that originated in the use of firearms, the gold is melted in the producer's gold room, and any remaining black sand or other heavy minerals are skimmed off the top of the molten gold, as cream is skimmed from milk. Any lead or solder that was not removed by sieving or hand picking is melted with the gold and this decreases its fineness. Finally, the gold is poured into molds to form gold bricks, and the skimmings are later cyanided to recover adhering gold.

Native platinum, for several reasons, cannot be handled by these methods. The platinum metals are paramagnetic in varying degrees, as shown in table 3, and a part of the natural cubic alloys may be ferromagnetic; therefore, all the minerals of the black sand cannot be removed magnetically. Crude placer platinum is first separated from the black sand concentrates by the use of a Wilfley or some other type of concentrating table. Screening of the dried metals and magnetic separation so far as permitted are then employed. Finally, an ingenious system of blowing the product fed from a vibrating hopper is employed by the Goodnews Bay Mining Co., by means of which successive fractions of the platinum alloys are collected in sectionalized boxes. This process, in a repetitive flowsheet, eliminates most of the remaining black sand and yields a product that contains about 11 percent of impurities. This final product is not melted by the producer, owing partly to the high melting temperatures of the platinum metals and partly to the fact that osmium and, to a lesser degree, ruthenium sublime. Melting would thus produce losses in osmium and ruthenium, and would in addition generate the poison-

TABLE 5.—*Natural isotopes of the platinum metals, gold, and silver*

[M=mass number; P=number of protons; N=number of neutrons]

Platinum (P=78)			Iridium (P=77)			Osmium (P=76)			Ruthenium (P=44)			Rhodium (P=45)			Palladium (P=46)			Gold (P=79)			Silver (P=47)		
M	N	Percent	M	N	Percent	M	N	Percent	M	N	Percent	M	N	Percent	M	N	Percent	M	N	Percent	M	N	Percent
190	112	0.012	191	114	38.5	184	108	0.018	96	52	5.68	103	58	100.0	102	56	0.8	197	118	100.0	107	60	51.35
192	114	.78	193	116	61.5	186	110	1.59	98	54	2.22				104	58	9.3				109	62	48.65
194	116	32.8				187	111	1.64	99	55	12.81				105	59	22.6						
195	117	33.7				188	112	13.3	100	56	12.70				106	60	27.1						
196	118	25.4				189	113	16.1	101	57	16.98				108	62	26.7						
198	120	7.23				190	114	26.4	102	58	31.34				110	64	13.5						
						192	116	41.0	104	60	18.27												

These eight atoms have four isobars, eight isotones, and 11 isodiaspheres, as follows:

The isobars are: ${}_{78}Pt^{190}$, ${}_{76}Os^{190}$; ${}_{78}Pt^{192}$, ${}_{76}Os^{192}$; ${}_{44}Ru^{102}$, ${}_{46}Pd^{102}$; ${}_{44}Ru^{104}$, ${}_{46}Pd^{104}$.

The isotones are: ${}_{78}Pt^{196}$, ${}_{79}Au^{197}$; ${}_{78}Pt^{194}$, ${}_{77}Ir^{193}$, ${}_{76}Os^{192}$; ${}_{78}Pt^{192}$, ${}_{77}Ir^{191}$, ${}_{76}Os^{190}$; ${}_{78}Pt^{190}$, ${}_{76}Os^{188}$; ${}_{46}Pd^{108}$, ${}_{47}Ag^{109}$; ${}_{44}Ru^{104}$, ${}_{46}Pd^{106}$, ${}_{47}Ag^{107}$; ${}_{44}Ru^{102}$, ${}_{45}Rh^{103}$, ${}_{46}Pd^{104}$; ${}_{44}Ru^{100}$; ${}_{46}Pd^{102}$.

The isodiaspheres are: ${}_{78}Pt^{196}$, ${}_{76}Os^{192}$; ${}_{78}Pt^{195}$, ${}_{77}Ir^{193}$, ${}_{79}Au^{197}$; ${}_{78}Pt^{194}$, ${}_{76}Os^{190}$; ${}_{77}Ir^{191}$, ${}_{76}Os^{189}$; ${}_{78}Pt^{192}$, ${}_{76}Os^{188}$; ${}_{78}Pt^{190}$, ${}_{76}Os^{186}$; ${}_{44}Ru^{104}$, ${}_{46}Pd^{108}$; ${}_{44}Ru^{102}$, ${}_{46}Pd^{106}$; ${}_{44}Ru^{101}$, ${}_{45}Rh^{103}$, ${}_{47}Ag^{107}$; ${}_{44}Ru^{100}$, ${}_{46}Pd^{104}$; ${}_{44}Ru^{98}$, ${}_{46}Pd^{102}$.

ous gas OsO_4. Therefore, the final product is shipped in bulk to the refiner, where it is analyzed and processed by chemical treatment. Every cleanup from the dredge of the Goodnews Bay Mining Co. is thus processed and separately analyzed.

CHEMICAL PROPERTIES AND ANALYSES

Pure platinum is not attacked by the common inorganic acids, but is dissolved, though less readily than gold, by aqua regia. On the other hand, pure iridium and rhodium are not appreciably attacked by aqua regia or other inorganic acids, and osmium and ruthenium are quite insoluble in such acids. Palladium is dissolved not only by aqua regia but also by hot nitric or hot sulfuric acid. This vulnerability of palladium to acids is reflected in its inferior ability to withstand the effects of weathering and consequently by its superior tendency to form natural mineral compounds.

The platinum metals occur commonly in bedrock as two distinct alloys, which usually are intergrown in a pseudoeutectic fabric, but may also occur separately. As obtained from placer deposits, however, these two alloys are invariably mixed, and any chemical analysis of placer platinum therefore represents the sum of two different products, intermingled in an unknown ratio. Only rarely is it possible to obtain a pure sample of either alloy. Chemically, these alloys behave differently, in their reactions with acids and other reagents, than the purified platinum metals, and moreover, these reactions are not quantitatively predictable, because they depend upon the compositions of the alloys, which are inconstant. Hence, even the best analyses will fail to show either the composition of the individual alloys or their existing ratios, though certain guiding principles, hereafter enumerated in discussing different placers, may render possible a general understanding of the natural and proportions of the component alloys.

Bulk samples of the platinum metals from placers are prepared for analysis, and also subsequently for refining, by dissolving them in hot aqua regia. In this procedure, most of the platinum, parts of the iridium and rhodium, and all the palladium are dissolved, but the osmium and ruthenium are unaffected and have to be gotten into solution by another method. The proportions of the soluble and insoluble fractions vary with different samples, according to the composition of the component alloys and their ratios, so that no general statement is warranted. In a typical sample of the platinum alloys recovered by the Goodnews Bay Mining Co., Alaska, it was found that 98.1 percent of the platinum, 18.5 percent of the iridium, 66.7 percent of the rhodium, and all the palladium were dissolved in hot aqua regia. The remainder of the platinum, iridium, and rhodium and all the osmium and ruthenium constitute an insoluble fraction that is otherwise processed.

The solubilities of the platinum metals in one another and in certain base metals has an important bearing upon the composition of their natural alloys. Gold and silver, in laboratory preparations, are miscible in all proportions, with well-defined solidus and liquidus curves, yet, the proportion of gold in native gold-silver alloys is rarely less than 60 percent, as shown by Mertie (1940, p. 93–124). The explanation of this phenomenon may be related to the formation of such alloys as hydrothermal rather than magmatic products. The platinum metals have different crystallographic properties that limit the amounts of these metals and the dross that constitute the two principal alloys. Thus the cubic platinum metals show continuous solidus and liquidus curves, but they appear not to be miscible in all proportions in nature, though the limits of natural miscibility have not been determined. Apparently, however, these limits are not dependent upon their mode of formation, as the natural alloys are dominantly of magmatic origin. Platinum and palladium have continuous solidus-liquidus curves for binary alloys of each of these metals with gold, silver, copper, iron, nickel and cobalt, so that the base elements may readily constitute the dross, if they were originally present in the magma. Other variations, however, result from local conditions in the bedrock sources, so that the compositions of the natural alloys are markedly inconstant. The platinum minerals are likewise variable in composition, but the variations are much smaller than in the alloys.

Much less is known of the natural limits of miscibility of the hexagonal elements osmium and ruthenium with the other platinum metals and with the base metals. Melted mixtures of platinum or palladium with osmium or ruthenium show only partial solidus-liquidus curves, which give place at some point to more than two phases. Natural alloys of osmium and ruthenium contain amounts of iridium that commonly exceed those of the osmium, and such alloys also contain small amounts of rhodium and platinum. The amount of platinum, however, may range upward to 15 percent, though a tenor as great as this suggests that the analysis was made on a mixed sample of the two alloys. Palladium is generally absent or present only as a trace. The solubilities of the base metals in these hexagonal alloys is apparently slight, as alloys of osmiridium invariably contain small amounts of dross. In general, the limits of these ranges in mis-

cibility are different from those producible in the laboratory and have not yet been determined.

The separation of the platinum metals into soluble and insoluble fractions for analysis has already been mentioned. The insoluble fraction is reduced by repeated treatments with alkaline oxidizing fluxes, and thereafter is gotten into solution. For scientific comparisons, these two fractions may be separately analyzed, as was done for the writer in 1945 by Johnson, Matthey and Co. with a sample of platinum metals contributed by the Goodnews Bay Mining Co., Alaska. Ordinarily, however, the soluble and insoluble fractions are combined for final analysis. The presence of black sand that cannot entirely be removed from placer platinum metals has already been noted. These remaining minerals go into solution at the refineries, either in the aqua regia, or along with the insoluble fractions that are treated with fluxes. Hence invariably there is given, even in superior commercial analyses, a percentage of "impurities." This item includes the base metals that constitute the dross of the platinum alloys, the dross of any free gold that may be present, any lead shot, solder, or similar materials not recognized by the producer, and the base metals of the included black sand. Recent investigations have also shown that minute grains of chromite, chalcopyrite, and other minerals are intergrown in some of the natural platinum alloys. Thus in the platinum metals of the Goodnews Bay Mining Co., grains of chromite and chalcopyrite are clearly visible in polished sections at magnifications as low as 50 diameters. These facts lead to the conclusion that the true dross of natural platinum alloys, even in handpicked samples, is difficult to determine with precision.

Chemical analyses of the natural platinum alloys are of different classes, with different degrees of dependability. Analyses are divided by the writer into two general classes, which are designated as superior and inferior analyses. Superior analyses are considered to be those wherein the percentages of all the component platinum metals are determined, with or without the base metals of the dross. Exceedingly few such analyses are available of the platinum metals produced in foreign countries. Numerous analyses of this kind have been made by the U.S. Bureau of Standards, and one was made by the U.S. Geological Survey. Most assayers are incapable of making high-grade analyses of the platinum metals and alloys, and concerns which are capable of doing such analytical work do not always do so, as the cost may be prohibitive. Another reason why such analyses, if made, are not published is that it may be to the advantage of either the producer or the processor, or both, that such results should not be generally known. The best analyses available to the writer are those made by Johnson, Matthey and Co., Inc., of Malvern, Pa., for the Goodnews Bay Mining Co. of Alaska. Few other superior analyses appear in this report.

Inferior analyses include two general types. One type, which is the most prevalent, is essentially an analysis of only that part of the sample which dissolves in hot aqua regia. The insoluble fraction, whose total weight is known, is presented as osmium plus iridium, or perhaps as osmiridium. It commonly contains more iridium than osmium, as well as ruthenium and small amounts of platinum and rhodium. Therefore in such inferior analyses, the tenors of platinum, iridium, and rhodium are too low, and the tenor of ruthenium is neglected and rarely mentioned. Only the percentage of palladium is correct. The analyses of the platinum metals from Russia, because one part of the iridium is separately stated, whereas another part is reported as osmiridium, appear to be of this type; many other analyses in this report are of similar character.

A second type of inferior analysis is one wherein only the soluble platinum and palladium are reported and the soluble iridium and rhodium are added either to the platinum or to the insoluble fraction reported as iridium plus osmium. This procedure is common practice where the alloy contains only small amounts of iridium, osmium, ruthenium, and rhodium. Such analyses have little value, but they cannot be ignored, because they show at least the tenor in palladium and a minimum tenor in platinum. Examples of these are shown by the two mean analyses of Colombian platinum published by Singewald (1950, p. 174).

The problem thus arises how to present and interpret chemical analyses that are available in the literature. If, in addition to the percentages of some or all the platinum metals, the contents of copper, iron, and other base metals are specifically stated, the latter percentages cannot be ignored, and are stated as a part of the analysis with the implicit understanding that these tenors do not necessarily represent dross. If percentages of the base metals are not given, the gold (which is commonly free gold) is deleted, and the analysis is recomputed in terms of the platinum metals to total 100 percent. Even, however, if the tenors of the base metals are given, such recomputed analyses of the patinum metals alone serve a useful purpose in comparing different alloys with one another.

MINERALOGY

The platinum metals occur in nature in two forms: first, as natural alloys and intergrowths of alloys, and second, as chemical compounds in which the platinum metals function as cations. The alloys are solid solutions and have as wide ranges in composition as their crystallography and other factors permit. The chemical compounds also have variable compositions but within smaller limits, as these are controlled by substituions of cations and anions with comparable radii. Wright and Fleischer (1965, p. A5–A6) have tabulated as compounds, or mineral species, the platinum metals known to be chemically combined with oxygen, sulfur, arsenic, antimony, bismuth, tin, or tellurium, if these elements function as anions. Recognizing, however, the uncertainty that exists in a definite classification of the platinum metals, they have tabulated all nonminerals as "alloys and intermediate compounds." The tabulation in this report is twofold, comprising alloys and minerals, with a reservation that a few of the so-called alloys may be partly or wholly minerals and vice versa. Moreover, in listing the alloys, preference is given to terms that indicate mixtures and intergrowths of platinum metals or alloys, as opposed to terms ending in "ite," which connote platinum minerals.

NATURAL ALLOYS OF PLATINUM METALS

The native platinum metals, found mainly in placer deposits, consist generally of two principal alloys, which occur either separately or intergrown with one another. These alloys are designated commercially and generically as "platinum" and "osmiridium." Platinum consists dominantly of that metal, but includes invariably the other five metals in variable amounts. Osmiridium consists dominantly of iridium and osmium, but includes also the metals ruthenium, rhodium, and platinum.

Samples of the platinum metals taken from placers are heterogeneous for a number of reasons. First, the two alloys do not have constant compositions, but instead vary from one site in bedrock to another. Second, the proportions of one alloy to another vary from place to place, and if they are intergrown, as they commonly are, the ratios of the two alloys in grains and nuggets are inconstant. Third, it is commonplace that very minute grains of one alloy, measurable perhaps in microns, may be present in another, and this is one reason why it is almost impossible to obtain pure samples of either alloy for chemical analysis. Fourth, platinum-bearing minerals may also be included; in fact, laurite has been found in one of the alloys of the platinum metals in the Goodnews Bay district. Fifth, chromite is commonly either attached to or intergrown with the platinum alloys, and there are also minute inclusions of base minerals, wherein iron and copper are the principal cations, as exemplified by chalcopyrite. And finally, metallic iron and copper are invariably alloyed with the platinum metals, to form the dross. Bulk samples of the platinum metals recovered from placers therefore necessarily contain variable proportions of the six platinum elements, and chemical analyses, even superior analyses, have a limited value in deriving scientific conclusions regarding the compositions and interrelations of the alloys. Such analyses, however, may lead to important deductions relating to the origin and formation of the placers, and they are, of course, indispensable for commercial valuation of the platinum metals.

It is virtually impossible, for the reasons stated, to obtain pure samples of either of the two alloys, and the closest approximations appear to be in their electromagnetic separations. Osmium, iridium, and ruthenium have small magnetic susceptibilities, as is evident from table 3; osmiridium, composed mainly of these three elements, likewise has a low paramagnetism. The separation of a placer sample in an intense magnetic field yields one product that is mainly osmiridium, though minute intergrowths and inclusions of the principal alloy may also be present. Naturally, this method is more practicable if the sample is first sieved, and grains of −200 mesh are selected for the electromagnetic separation.

It follows, from the foregoing considerations, that specific mineralogical names of alloys, even of a single purified alloy, are not warranted, as an indefinite number of such terms could be applied. Nevertheless, numerous such designations have been used, according to the ideas of different writers. The better known of these names are shown in table 6, even though they include duplications and improper designations, and many of them do not conform to the definition of a mineral species. The six platinum metals are not specifically tabulated, as they do not occur in nature free of one another. The names platinum and palladium are used, however, as generic terms. It may be added that gold should also be used as a generic term, as pure gold, free of silver and dross, is not present in nature.

The names osmiridium and iridosmium have been used by Palache, Berman, and Frondel (1944, p. 112) with meanings the reverse of those given in the preceding table. This has led to confusion, as the reader may be uncertain of the meaning intended by the writer. The products from the Witwatersrand and from Tasmania are alloys that contain more osmium

TABLE 6.—*Alloys of platinum metals*

Platinum (generic term):
- Cuproplatinum, cupric platinum.
- Ferroplatinum. Ferric platinum with 10–30 percent Fe.
- Nickel platinum, nickelic platinum.
- Noril'skite, containing Pt, Pd, Ni, Fe, and Cu.
- Palladiplatinum, palladic platinum. Pd=Pt, approximately.
- Platinic iron.
- Platiniridium, platinic iridium, avaite.
- Polyxene. Platinum with less than 10 percent Fe, and therefore a synonym of platinum.
- Rhodic platinum.
- Stannic platinum, stannoplatinite.
- Unnamed alloys described by Genkin (1959) and Borovskii, Deev, and Marchukova (1959).
  - A. Contains Pt, Sn, Ir, Pd, and Fe.
  - B. Contains Pt, Pd, Sn, and Ir.
  - C. Contains Pt, Fe, Ir, Ni, Cu, and Ag.

Palladium (generic term):
- Allopalladium, eugenesite. Contains Pd, Pt, Ru, and Cu, and traces of other elements.
- Platinum amalgam, potarite. PdHg or Pd_3Hg_2.
- Unnamed alloy described by Genkin (1959) and Borovskii, Deev, and Marchukova (1959).
  - D. Contains Pd, Pb, and Ag.

Osmiridium, (Ir>Os):
- Auric osmiridium, aurosmirid, aurosmide. Contains up to 19 percent Au.
- Platinic osmiridium, platinosmiridium.
- Rhodic osmiridium, rhodosmiridium.
- Ruthenic osmiridium, ruthenosmiridium. Contains up to 21 percent ruthenium.

Iridosmium, iridosmine (Ir<Os):
- Osmite, synonym of iridosmine.
- Platinic iridosmium, platiniridosmine.
- Rhodic iridosmium, rhodiridosmine.
- Ruthenic iridosmium, rutheniridosmine.

Nevyanskite (Ir 50–80 percent):
- Varieties of nevyanskite, according to tenors of the other platinum metals.

Siserskite, sisserskite, sysertskite, (Ir 20–50 percent):
- Varieties of siserskite, according to tenors of the other platinum metals.

Alloys of gold and platinum metals:
- Platinic gold.
- Iridic gold.
- Rhodic gold, rhodite. Contains up to 43 percent rhodium.
- Palladic gold, porpezite. Contains up to 10 percent palladium.

than iridium, and are therefore properly called iridosmine, if use is made of that term. A commercial designation is needed, however, for alloys consisting dominantly of iridium and osmium, regardless of the relative proportions of these two metals. For this purpose, the writer uses the term "osmiridium," because the amount of iridium is generally greater than that of osmium, but for scientific descriptions, both osmiridium and iridosmine are employed.

The terms "osmiridium" and "iridosmine" are not necessarily correlative with "nevyanskite" and "siserskite," because the numerical definitions of the two latter terms do not state whether they refer to analyses with dross or to analyses recomputed free of dross. Without this refinement, an alloy called nevyanskite may in fact be siserskite and vice versa. These names ending in "ite" are also objectionable because they suggest the definite compositions of minerals, whereas they are in fact alloys with widely divergent compositions. Osmiridium and iridosmine are preferable terms.

CHEMICAL COMPOUNDS OF PLATINUM METALS

The platinum metals also occur as chemical compounds, to which specific names have properly been applied. The platinum minerals may also include more or less copper, lead, tin, nickel and cobalt, and it is inferred that these elements substitute as cations for the platinum metals. If iron and chromium are reported, it is generally assumed that they are impurities resulting from an admixture with traces of other minerals, and even nickel and cobalt may sometimes belong in this category. The common base-forming elements are arsenic, antimony, bismuth, sulfur, tellurium, oxygen, and possibly other anions, such as selenium, but tin and lead may also function as anions instead of cations. The absence of a base-forming element indicates an alloy rather than a mineral, but as some elements may be either acid forming or base forming, it is sometimes difficult to decide whether certain combinations of elements represent alloys or minerals. A low percentage of tin or lead, however, suggests that these elements are present as cations.

The platinum minerals differ from the platinum alloys in one important respect. The principal platinum alloy, designated generically as platinum, contains generally all six of the platinum metals, though osmium and ruthenium may be present only in small amounts. Osmiridium contains five of the platinum metals, and by careful analysis, palladium may also be identified. The platinum minerals, on the other hand, contain fewer of the platinum metals, and it has not been proven that all of them are ever present.

Numerous platinum minerals have been discovered in recent years, notably since 1958. The principal investigators and discoverers, as shown in the accompanying bibliography, were J. E. Hawley, A. D. Genkin, E. F. Stumpfl, N. N. Zhuravlev, O. E. Zvyagintsev, and their several collaborators. Genkin (1959) recognized eight platinum minerals in the ores of the Noril'sk district, northwestern Siberia, which were identified by Borovskii, Deev, and Marchukova. Three of these proved to be platinum, alloyed with iridium, iridium and iron, or palladium, and a fourth was pal-

ladium, alloyed mainly with lead. The other four are listed as unnamed minerals. Stumpfl, in 1961, identified nine additional platinum minerals in the ores of the Driekop Mine, Transvaal, Republic of South Africa, of which one was named geversite. The other eight are listed as unnamed minerals.

The platinum minerals, as now known, are tabulated in table 7.

TABLE 7.—*Platinum minerals, named and unnamed*

Mineral	Composition	Reference
Named minerals		
Arsenopalladinite	Pd_3As	
Braggite	(Pt, Pd, Ni)S	Bannister (1932a).
Cooperite	(Pt, Ni, Pd)S	Cooper (1928).
Froodite	$PdBi_2$	Hawley and Berry (1958).
Geversite	$PtSb_2$	Stumpfl (1961).
Hollingsworthite	$(Rh, Pt, Pd) (As, S)_2$	Stumpfl and Clark (1965).
Ruthenian hollingsworthite	$(Rh, Ru, Pt) (As, S)_2$	Genkin, Zhuravlev, Troneva, and Muraveva (1966).
Irarsite	(Ir, Ru, Rh, Pt) (As, S)	Do.
Kotulskite	$Pd(Te, Bi)_{1-2}$	Genkin, Zhuravlev, and Smirnova (1963).
Laurite	$(Ru, Os)S_2$	Wöhler (1866).
Michenerite	(Pd, Pt) (Bi, Te)	Genkin, Zhuravlev, and Smirnova (1963).
Moncheite	$(Pt, Pd) (Te, Bi)_2$	Do.
Niggliite	Pt (Te, Sn)?	
Palladinite (Palladite)	PdO	
Sperrylite	$PtAs_2$	
Rhodian sperrylite	$(Pt, Rh, Ir, Pd) (As, S)_2$	Stumpfl and Clark (1965).
Stannopalladinite	$(Pd, Pt, Cu)_3 Sn_2$	
Stannoplatinite	Pt_3Sn_2	Mikheev, Kalinin, and Sal'dev.
Stibiopalladinite	Pd_3Sb	Adam (1927).
Vysotskite	(Pd, Ni)S	Genkin and Zvyagintsev (1962).
Zvyagintsevite (Zvyaginzevite)	$(Pd, Pt)_3 (Pb, Sn)$	Genkin and Korolev (1961); later Genkin, Muraveva, and Troneva (1966).

Unamed minerals

Composition	Reference	Composition	Reference
$PtBi_2$ (Not michenerite nor moncheite).	Hawley and Berry (1958).	Pt(Sb, Bi)	Stumpfl (1961).
Pt_3Sn_3	Ramdohr (1960).	$Pd_7(Sb, As)_3$	G. A. Desborough (written commun. 1969).
$(Pt, Sn) As_2$	Genkin (1959), Borovskii, Deev, and Marchukova (1959).	Pd(Sb, Bi)	Stumpfl (1961).
$(Pt, Os, Ru) As_2$	Do.	$(Pd_2Cu)Sb$	Do.
PdS_2	Do.	$(Pd_3Cu)Sb_3$	Do.
$(Pt, Ir) As_2$	Stumpfl (1961).	$(Pt_4Cu_4)Sn_3$	Do.
$(Pt, Ir, Os) As_4$	Do.	PdBi	Hawley (1962).
PtSb	Do.	Pd_3 Pb	Cabri and Traill (1966).
		Pd(Bi, Pb)	Do.

Sperrylite, the most plentiful and widely distributed of the platinum minerals, is a tin-white brittle cubic mineral with a black streak, a hardness of 6–7, and a specific gravity of 10.58. Is is highly resistant to atmospheric weathering. Sperrylite consists mainly of platinum chemically combined with arsenic, but contains also a small percentage of rhodium. Three analyses of sperrylite are known to the writer. These analyses, recomputed free of gangue and other impurities to total 100 percent, are shown in table 8. The sperrylite from the Vermilion mine is very close to the theoretically computed values of platinum metals and arsenic.

TABLE 8.—*Analyses, in percent, of sperrylite*

[N.D., no data]

	A	B	C	Mean	Theoretical composition
Platinum	55.77	56.89	58.06	56.49	56.58
Rhodium	.76	1.72	N.D.	1.24	
Palladium	Tr.				
Arsenic	43.47	41.39	41.94	42.27	43.42
Total	100.00	100.00	100.00	100.00	100.00

A. Vermilion mine, Sudbury district, Canada, mean of two analyses (Coleman, 1905, p. 100).
B. Tweefontein, Potgietersrust district, Republic of South Africa (Wagner, 1929, p. 17).
C. Timpton Valley, Amur Province, southeastern Siberia (Quiring, 1962, p. 193).

Two spectrographic analyses of sperrylite (Lewis, 1950) from the Falconbridge mine in the Sudbury district are given in table 9. The nickel and copper may be contaminants. The principal item of interest

TABLE 9.—*Spectrographic analyses of sperrylite from Falconbridge mine, Sudbury district, Ontario*

[The symbols indicate intensity of spectral lines according to the following arbitrary scale. Mc, major constituent; Vs, very strong; S, strong; M, moderate; W, weak; Tr, trace. Cited from Lewis, 1950]

	S-67	*S-78*
Platinum	Mc	Mc
Palladium	Tr	W
Arsenic	Mc	Mc
Antimony	Tr	W
Gold	W	M
Tin	Tr	W
Bismuth	M	S
Silver	M	S
Zinc	Tr	Tr.
Copper	Vs	S
Nickel	Tr	W
Iron	W	
Silicon	M	M
Magnesium	W	M
Calcium	M	M
Cadmium		Tr.

in these analyses is the essential absence of palladium. This indicates that sperrylite is not a major source of palladium, and therefore that other palladium-bearing minerals are present in the ores of the Sudbury district, Ontario. Another noteworthy feature is the absence of rhodium in Lewis's two analyses, whereas rhodium appears in two of the analyses in table 8.

Sperrylite, in addition to its cited occurrences, has also been reported from the Broken Hill district, New South Wales, Australia; from the Great Eastern mine in Clark County, Nev., from the Rambler and Centennial mines, Albany County, Wyo.; from certain tributaries of the Little Tennessee River, Macon County, N.C., and from other localities.

Cooperite, braggite, laurite, potarite, allopalladium, palladinite, stibiopalladinite, and niggliite are little known platinum minerals. Cooperite, braggite, and stibiopalladinite have been described from the Transvaal, Republic of South Africa. Laurite also occurs in the Transvaal and in Siberia but was first discovered in placer sands along the foothills of the Bobaris Mountains in Southeast Borneo. It later was reported from Colombia and Oregon. Potarite was described first from Guyana (formerly British Guiana), and was reported to be a chemical combination of palladium and mercury, but is classified in this report as a palladium amalgam. Allopalladium (eugenesite) is also included as an alloy. A surficial coating on a porpezite from Brazil was called palladinite and was assumed to be PdO, but no analysis is recorded. Niggliite is a rare mineral that was first found near Insizwa, East Griqualand, Republic of South Africa, about 300 miles south of Johannesburg. The other platinum minerals that are listed have been discovered in recent years and have been described in papers cited in the accompanying bibliography.

The list of platinum minerals presented above indicates that palladium is more prevalent than platinum in mineral compounds. This is expectable, as palladium is much less resistant to acid and alkali solvents than the other platinum metals. A large part of the palladium recovered at Sudbury and in the Transvaal is believed to occur as discrete minerals associated with the sulfides of the basic and ultrabasic host rocks. Mention should also be made of the fact that some of the platinum metals occur as atomic replacements of elements in the various ore minerals, and even in rock-forming minerals such as peridotite, perknite, gabbro, and their variants. Analyses of pyrrhotite, pentlandite, chalcopyrite, bornite, chromite, columbite, cassiterite, stannite, molybdenite, galena, freibergite sphalerite, sylvanite, hessite, and other minerals show that small amounts of the platinum metals may be present, if the atomic radii of the cations are not too different. The platinum metals may also occur as interstitial solid solutions in various minerals and ores.

PLATINUM DEPOSITS

DISTRIBUTION

The platinum metals have been found as natural alloys in many countries, notably in the Russian Urals, in Colombia, and in Alaska, but few other countries have had significant productions. Platinum lodes are uncommon, yet the bulk of the world's production is now coming from such deposits. The major sources are in the Union of Soviet Socialist Republics, in the Republic of South Africa, and in Canada; and the ores from these countries are described in considerable detail. The gold-platinum placers of Colombia have not been adequately described, but owing to their historical significance, they are treated as fully as the available data permit. The placers of the Goodnews Bay district, Alaska, are described in more detail than their size and production appear to warrant, for the following reasons. First, they are the only commercial platinum deposits in the United States, and are therefore of national importance; second, more statistical and genetic data on these placers are available than for any similar deposits elsewhere in the world; and third, an earlier report by the writer (1940) is now outdated and requires partial revision. The lithified placers of the Witwatersrand, Republic of South Africa, are given more attention than their production would appear to justify, because they are the world's principal source of osmiridium. Deposits that

are small producers of the platinum metals, and others that were formerly productive but are now exhausted, are described in such detail as their scientific interest appears to warrant. Nonproductive deposits in the United States are given more attention than similar deposits in foreign countries.

TABLE 10.—*Distribution of platinum metals*

- Albania
- Algeria
- Argentina
- Australia
  - New Guinea (Australian)
  - New South Wales
  - Queensland
  - Tasmania
  - Victoria
- Brazil, 6 states
- Burma
- Canada, 10 provinces
  - Alberta
  - British Columbia
  - Manitoba
  - Newfoundland
  - Northwest Territories
  - Nova Scotia
  - Ontario (principal deposits)
  - Quebec
  - Saskatchewan
  - Yukon
- Ceylon
- Chile (Island of Chiloe)
- China (Mongolia)
- Colombia, 2 departments
  - Choco
  - Nariño
- Cuba
- Czechoslovakia
- Dominican Republic
- Ecuador
- Egypt
- Ethiopia
- Finland (Lapland)
- France
- Germany
- Ghana
- Great Britain
  - Cornwall
  - Ireland
  - Scotland
- Greenland
- Guatemala
- Guiana (French)
- Guyana
- Honduras
- Hungary
- India
  - Assam
- Indonesia
  - Borneo
  - Java
  - Sumatra
- Iran
- Italy
- Kenya
- Malagasy Republic (Madagascar)

- Malawi (formerly Nyasaland)
- Mexico
- New Caledonia
- New Guinea
  - Papua
  - Territory of New Guinea
- New Zealand
- Norway
- Panama
- Peru
- Philippine Islands
- Portugal
- Puerto Rico
- Republic of the Congo
  - Katanga
- Republic of South Africa
  - Cape of Good Hope Province
  - Orange Free State
  - Transvaal
- Rhodesia
- Romania
- Sierra Leone
- Somali Republic
- Spain
- Surinam
- Sweden
- Union of Soviet Socialist Republics
  - Noril'sk district
  - Petsamo district
  - Ural Mountains
  - Other districts
- United States (12 States)
  - Alaska
    - Goodnews Bay district
    - Twenty-one other localities
  - Arizona, 3 counties
  - Arkansas
  - California, 34 counties
  - Colorado, 5 counties
  - Delaware
  - Georgia
  - Idaho, 8 counties
  - Maryland (Baltimore County)
  - Missouri
  - Montana, 5 counties
  - Nevada, 3 counties
  - New Mexico
  - New York
  - North Carolina, 3 counties
  - Oregon, 13 counties
  - Pennsylvania
  - South Dakota
  - Texas
  - Utah, 2 counties
  - Washington, 6 counties
  - Wyoming, 3 counties
- Venezuela

Platinum metals have been found in 22 States of the United States, but only Alaska has become a major producer. In California and Oregon, platinum has been recovered in relatively small amounts as a byproduct of gold placer mining, and in several of the Rocky Mountain States, small gold-platinum or copper-platinum lodes have been mined, generally without a profit. Few of the occurrences of platinum metals in the United States merit description, but because such deposits exist in this country, all the principal ones are more fully described than similar deposits would be in foreign countries.

The principal countries in which platinum metals have been found are listed alphabetically in table 10, but most of these occurrences are so rare or freakish that they require no description in this report.

Spectrographic research has greatly multiplied the known habitats of the platinum metals. In fact, traces of these elements in rocks and minerals are becoming so commonplace that it is difficult to learn and tabulate all the new occurrences. Minerals and rocks that contain traces of the platinum metals have been tabulated by Wright and Fleischer (1965, p. A9 and A13). The platinum metals also occur in some meteorites and in the gases surrounding the sun, and they have been identified both in marine organisms and in sea water.

CLASSIFICATION

The platinum metals occur in workable deposits mainly as platinum minerals in nickel-copper and copper lodes and as platinum alloys in placers, but they occur also in other environments that are of more scientific than economic interest. The principal workable lodes are in Ontario and Manitoba, Canada, in the central Transvaal, Republic of South Africa, and in several areas of northwestern Siberia, U.S.S.R. To these should be added the lithified placers of the Witwatersrand, Republic of South Africa. Most of the workable lodes are characterized by platinum and palladium minerals, but some of them, notably in the Transvaal, also yield small amounts of the native metals or alloys.

LODES

The platinum metals occur as lodes in several different environments. The more significant deposits are related to the basic or ultrabasic rocks, but these metals are also found in ores that are related to granitic rocks, as shown in the following classification:

CLASSIFICATION OF PLATINUM LODES

A.—Platinum-bearing nickel-copper, copper, or copper-cobalt sulfides that are related genetically to basic or ultrabasic rocks, commonly the former, but are not magmatically segregated ores. The workable lodes occur principally as secondary concentrations of ore minerals rather than as magmatic minerals in situ, though the secondary ores appear to grade into disseminated ore minerals in the associated igneous rocks. The ore bodies occur either along the contact of the basic intrusives with country rock, or at variable distances up to 5 miles from the basic intrusives. These ores may or may not be associated with igneous rocks, of which some are considered to be related genetically to the parent basic rocks. By some geologists, the sulfides of these secondary deposits are thought to have originated as immiscible fluids of magmatic character; by others, these sulfides are considered to be epigenetic hydrothermal deposits. The ores of the Sudbury district, Ontario, exemplify such deposits. Native platinum metals or their alloys are commonly absent from deposits of this type.

B.—Platinum-bearing nickel-copper ores that are magmatically disseminated or concentrated in gabbroic and ultrabasic rocks. Pyroxenite and anorthosite the principal source rocks are commonly associated with norite and all of these may have the outlines of dikes, sills, pipes, lenses, or schlieren. These rocks are petrographically homogeneous along their major structures for long distances but they vary locally and produce layers and lenses of peridotite and chromite. The platinum metals occur mainly in sperrylite, cooperite, and other platinum and palladium minerals, but smaller amounts of the native platinum metals or alloys are commonly present. The platinum minerals occur in the sulfides and in lesser amounts in the silicates and may be sufficiently plentiful to constitute the principal value of the ores, with byproducts of nickel copper, and other metals. The Merensky zone, in the Bushveld igneous complex of the Transvaal, illustrates this type of deposit. The ratios of platinum to palladium are significantly greater in the ores of class B than in those of class A.

C.—Native alloys of the platinum metals that are magmatically disseminated in peridotites, less commonly in perknites, and rarely in gabbros. If concentrated, they are commonly intergrown with chromite. Most of these deposits are in dunites, which range in composition from hortonolite dunite to olivine dunite. The dunites at some localities may be partly or wholly altered to serpentinite. The platiniferous hortonolite or iron-rich dunites are exemplified by the Onverwacht and Mooihoep properties in the Bushveld igneous complex of the Transvaal. Platiniferous dunites, perknites, and their alteration products are the sources of the Uralian placers; dunite and serpentinite are the sole sources of the placers of the Goodnews Bay dis-

trict, Alaska; and so far as known, similar peridotites and perknites are the sources of most placers that are known in the world. Platinum and osmiridium lodes have been discovered in dunite or serpentinite, principally in the Urals and in South Africa, but generally they have proven to be either too small or too low grade for profitable mining. Some masses of chromite, however, have been found in dunite that had high tenors in the platinum metals.

D.—Platinum minerals or native platinum alloys in copper and related ores indigenous to contact metamorphic and other types of ore bodies, including vein systems.

E.—Native platinum metals in the gold ores of quartz veins and in other ores of free gold. Twenty-three examples of such deposits are listed on page 98.

F.—Platinum-bearing meteorites.

G.—Secondary platinum metals:

1. Recovered in purification of blister copper and copper mattes that produced on a large scale.
2. Recovered at the U.S. Mint and other mints, in the refining of metallic gold. The U.S. Mints make no payment to the producers of gold bullion for such platinum metals, claiming them as seignorage.
3. Recovered from industrial wastes and from jewelry.

PLACERS

Platinum placers consist of alluvial deposits that contain in workable amounts the alloys of the six platinum metals, and it is worthy of note that no analagous deposits of platinum minerals have ever been found. The platinum metals occur commonly in two alloys of variable composition, of which one consists dominantly of platinum with varying amounts of the other five elements, whereas the other consists dominantly of iridium and osmium, less ruthenium, still smaller amounts of platinum and rhodium, and with little or no palladium. Much of the placer platinum consists of two intergrown or intermixed alloys, each of variable composition, as exemplified by the product recovered in the Goodnews Bay district and described on pages 84–87.

Some of the alluvial platinum comes from placers that yield both gold and platinum. The stream placers of Colombia and of California, later to be described, are excellent examples. Commonly the gold and platinum are separate alloys, one of gold and silver and the other of five or six platinum metals. This fact is not generally clarified by analyses of placer platinum, as small amounts of gold are reported merely as a part of the contained precious metals. Hence such analyses, in order to be comparable with others which show no gold, have to be recomputed free of gold as well as free of "impurities." Examples will later be given, however, of placer gold with which small amounts of the platinum metals are alloyed.

The densities of the platinum alloys found in placers and the sizes of their grains are generally similar to those of alluvial gold; hence, the geologic classification of platinum placers is exactly like that of the gold placers, as heretofore used by the writer:

A. Residual and eluvial placers.

B. Stream placers.
   1. Present stream valleys.
   2. Older stream valleys.
      a. Terrace deposits.
      b. Buried deposits.

C. Beach placers.
   1. Present beaches.
   2. Ancient beaches.
      a. Elevated beach deposits.
      b. Buried beach deposits.

D. Deltaic and outwash deposits.

E. Glaciofluvial (glaciofluviatile) deposits.

F. Aeolian deposits.

G. Lithified placers.

Placers of the platinum metals are commonly derived from dunite or serpentinite, less commonly perknite, in which these metals are sparsely and irregularly distributed. In nonglaciated regions, it may be inferred that the original lodes could be discovered by tracing the alluvial deposits upstream. Commonly the general country rock may thus be recognized, but workable lodes can rarely be located. This may result from one or more of the three following causes:

1. The original rocks from which the placers were derived may have been completely eroded, so that no platiniferous source rocks remain in the area.
2. The present country rock may be platiniferous, but may represent the uneroded low-grade roots of lodes that were much richer in their apical horizons.
3. All the original source rocks may have been of extremely low grade, and the placers may have been concentrated from such sources over a very long period of time. Under such circumstances, representative source rocks, even if preserved, would not constitute workable lodes and are not likely to be discovered.

The formation of placers is possible under any of these conditions. But workable lodes can rarely be located in placer fields, and it is therefore concluded that the platinum metals in placers have been concen-

trated generally from source rocks wherein these metals were sparsely and widely disseminated.

Heavy metals, such as platinum or gold, rarely migrate far downstream from their bedrock sources, unless they are so fine grained as to be moved by swift water or floated by surface tension. Flour gold, for example, may move downstream for many miles, in fact to the ocean. Generally, however, ordinary detrital grains of platinum or gold work rapidly downward through alluvial deposits, and come to rest either near, on, or within bedrock. If the bedrock has a well-developed cleavage or fracture, the precious metals may penetrate 10 feet or more. Only very high water that cuts to bedrock, or rejuvenation of a stream, will again move these metals, and even under these conditions, their downstream migration is not great. Hence, excepting some special environment, such as glaciation, placers of the precious metals may be assumed to lie within a few miles of their bedrock sources. If placer paystreaks are very long, it may be suspected either that several bedrock or proximate sources are present in a valley, or that the metals have been distributed downstream by repeated lowering of the base level of erosion or as result of glaciation.

CANADA

SOURCES AND PRODUCTION

Native platinum and osmiridum appear to have been discovered in Canada by T. Sterry Hunt (1852, p. 120) in concentrates recovered from the placers on Rivière du Loup and Rivière des Plants, tributaries of Chavdiere River, in southern Quebec. Platinum metals were subsequently found in 10 of the 13 provinces of Canada, though only a few of these deposits are or have been significant producers. No workable lodes of native platinum metals are known to exist, but numerous platinum- and palladium-bearing basemetal lodes and platinum-bearing gold placers have been discovered. Platinum-bearing and palladiumbearing sulfides, mainly in nickel-copper lodes, have been located in Alberta, British Columbia, Manitoba, Newfoundland, Northwest Territories, Nova Scotia, Ontario, Quebec, Saskatchewan, and Yukon. The most important of these are the nickel-copper deposits of the Sudbury district, in south-central Ontario, and those of north-central Manitoba, though similar lodes in the other provinces may in the future yield considerable amounts of the platinum metals.

Alluvial deposits containing the platinum metals are known in the provinces of Alberta, British Columbia, Quebec, and Yukon. In earlier years, the Tulameen district of British Columbia was an important producer of alluvial platinum, but these placers are now considered to be worked out, though certain fluvial deposits of greater thickness may sometime be mined. Small amounts of the platinum metals have also been recovered in other Canadian provinces, mainly as a byproduct of the mining of gold lodes and placers.

The total production of platinum metals from Canada for 1965 and 1966 came mainly from the Sudbury district, Ontario, but since 1962 has included also an output from the nickel-copper mine at Thompson, Manitoba, and lately a small output from a similar ore body near Lynn Lake, Manitoba, together with a minor byproduct from gold placers. The total production of platinum metals from all Canadian sources, up to and including 1966, has been about 11,440,000 troy ounces, with a maximum annual output in 1960 of 483,604 ounces.

ONTARIO

SUDBURY DISTRICT

DISCOVERY AND PRESENT MINING

The basic rocks of the Sudbury area were first observed by A. P. Salter, a Canadian Government surveyor, in 1857; and Alexander Murray, of the Canadian Geological Survey, verified the presence of these rocks in the same year. Copper sulfides were discovered by Thomas Flanagan in a gossan outcrop west of Sudbury in 1883, along the right-of-way then being opened for the Canadian Pacific Railroad; and in the next few years, most of the larger ore deposits of the district were found. The production of nickel and copper began in 1887. The platinum metals are a byproduct of the production of nickel and copper in the Sudbury district. Other byproducts that are now recovered include selenium, tellurium, gold, silver, cobalt, and iron.

Platinum, in the form of platinum diarsenide (sperrylite) was discovered at the Vermilion mine, in the Sudbury district, in 1885 by F. L. Sperry, a chemist of the Canada Copper Co., and this mineral was described and named by H. L. Wells (1889). As early as 1900, platinum was isolated in the ores of the Mond Nickel Co., and some platinum metals were extracted in subsequent years by Johnson, Matthey and Co., Ltd., in London. According to the Imperial Institute (1936, p. 62), the first recognized output from Canadian lodes was in 1919, when 25 ounces of platinum and 62 ounces of palladium were recovered.

The nickel-copper lodes of the Sudbury district are the principal sources of the platinum metals in Canada. These ores lie along or close to the margin of a synclinal basin of the basic igneous and overlying

sedimentary rocks, situated in south-central Ontario about 50 miles north of Georgian Bay, an arm of Lake Huron. Sudbury, which lies along the southeastern side of this basin, is a city of 35,000 people, which is reached by the Canadian Pacific and Canadian National Railroads as well as by first-class highways. An airport is located at the east side of the basin.

The important operating mines lie along or a short distance outside the margins of this synclinal basin. Most of these are now owned and operated by two companies, the International Nickel Co. of Canada, Ltd., and the Falconbridge Nickel Mines, Ltd. The International Nickel Co. of Canada, Ltd. owns the Creighton, Frood-Stobie, Crean Hill, Garson, Levack, Murray, Clarabelle (opencut), MacLennan, Totten, Copper Cliff, Copper Cliff North, Coleman, Kirkwood, Little Stobie, Blezard, Evans, Vermilion, Worthington, Victoria, Whistle, Shepard, and other mines, of which the first nine were producers in 1965. This company has concentrators at Copper Cliff and Creighton; smelters at Copper Cliff and Port Colborne, Ontario, and at Clydock, Wales; and precious metal refineries at Copper Cliff and at Acton, England (Mond Nickel Co.). The International Nickel Co. of Canada, Ltd. produces about 90 percent of the platinum metals recovered annually in the Sudbury district.

The Falconbridge Nickel Mines, Ltd. owns the Falconbridge, Falconbridge East, Hardy, Onaping, Fecunis Lake, Mount Nickel, McKim, Longvac, Longvac South, Strathcona, Lockberry, and other mines, of which the first five were productive in 1965. This company owns a smelter at Falconbridge, and the nickel-copper mattes are sent to their refinery at Kristiansand, Norway, for separation of the metals. The slimes from this process are refined, and the platinum metals recovered by the Englehard Industries, Inc., of Newark, N.J.

GENERAL GEOLOGY

The general geology of the synclinal basin, along whose margins lie the platinum-bearing nickel-copper ores, is difficult to interpret, as is indicated by the large volume of conflicting geological reports listed in the bibliography (p. 102–112). The synclinal basin is subelliptical in two-dimensional outline, with a spoon-shaped three-dimensional form, a length of about 37 miles, and a maximum width of about 17 miles. The direction of the major axis is about N. 65° E. The rocks dip generally toward the center of the basin, but the basin is asymmetrical in that the dips are commonly steeper along its southeast than along its northwest side. Locally, however, the steeper northwesterly dips along the southeast flank are reversed to the southeast. In detail, the structure is by no means simple, as the syncline, particularly along its southeast flank, is modified by minor folds and faulting. Surficially the central part of the basin shows low relief, but the igneous rocks that bound it cropout as low hills, which are designated locally as the north, east, south, and west ranges.

The igneous part of the basin consists of two peripheral sill-shaped masses of intrusive rocks, separated by a narrow transitional zone, with a total thickness estimated by Knight (1923) along the east range of about 8,300 feet. The lower mass of "norite" has a thickness of about 1,800 feet; the upper mass consists of micropegmatite or granophyre with a thickness of about 6,000 feet; and the transitional zone has a thickness of about 500 feet. Associated with the norite along its basal margin are quartz diorite and other intrusive rocks which are considered by Hawley (1962, p. 10) to be phases of the norite, though this interpretation is not universally accepted. The total relative thickness of the norite and the granophyre vary on the different ranges, as shown by the dips of the rocks and widths of the outcrops. Thus on the south range (southeast flank of the basin), the thickness of the two principal units appears to be less different than on the north range. The width of the total outcrop of the igneous rocks ranges from a minimum of 1¼ miles on the north range to a maximum of 4½ miles on the south range. The average total width on the north range is 1.9 miles and on the south range is 3.1 miles. These igneous rocks that delimit the Sudbury basin are said by Canadian geologists to be of late Huronian (Animikie) age.

The younger rocks inside the four ranges forming the central part of the basin, comprise a group of tuffaceous and sedimentary rocks called the Whitewater series, which, according to Cooke (1948), Yates (1948), Thomson (1957a) and other Canadian geologists, consists of the Onaping tuff, the overlying Onwatin slate, and the superjacent Chelmsford sandstone. A basal member of the Onaping tuff is the Trout Creek conglomerate or agglomerate. The thickness of the Whitewater series, owing to lack of outcrops, is known only approximately, but the Onaping tuff has been estimated to have a thickness of 5,000 feet, and the two overlying formations are believed to have a combined thickness of 3,700 feet. The Whitewater series is considered to be of late Huronian (Keweenawan) age.

Older sedimentary and igneous rocks underlie the noritic and associated intrusives. The stratigraphic succession of these rocks has been given by Knight

(1943), Cooke (1946), Yates (1948), and other Canadian geologists. According to these geologists, a group of sedimentary and igneous rocks, called the Sudbury or Timiskaming series, and believed to be of early Huronian age underlies the noritic irruptive. The formations of the Timiskaming series, named from top to bottom, are the Mississagi quartzite, the McKim graywacke and the Copper Cliff arkose, underlain by the Frood series. An ancient greenstone, originally of intrusive origin, overlies in places the Mississagi quartzite. These two formations, subjacent to the norite, are of importance in relation to the genesis of the nickel-copper lodes. The oldest rocks of this district, underlying the Frood series, compose the Stobie group, which consists of metamorphosed andesitic and basaltic lavas and quartzites.

The sequence above outlined is amplified by numerous intrusive rocks, notably by at least six types of granitic rocks. Two of these are granites, or granitic gneisses, that occur throughout the Sudbury series, and certain younger granitic rocks that intrude both the norite and the micropegmatite. Of special genetic interest is the quartz diorite that occurs at places along and near the contact between the norite and the underlying quartzite and greenstone.

INTRUSIVE ROCKS

The noritic rocks and associated intrusives, the overlying transition zone, and the micropegmatite at the top of this igneous sequence constitute what is known collectively as the "nickel irruptive" because they have been interpreted as related genetically to the nickel-copper ores. The distribution of the "nickel irruptive" is shown in figure 1. No general agreement exists, however, as to the mode of formation of the "nickel irruptive" nor as to its influence in the formation of the ore bodies. Bell (1891) was the first to recognize a closure of the igneous ring and the existence of the Sudbury basin. Walker (1897, 1935) conceived the idea that the "nickel irruptive" was a homogeneous intrusive which after its original placement was differentiated gravitatively into three units; Barlow (1904, 1906) corroborated this interpretation; and Coleman, in several reports (1905, 1907, 1913, 1916, 1923), carried this hypothesis to its ultimate development. The hypothesis was also adopted by Adams, Kemp, Roberts, Longyear, and others. Along with the idea of differentiation by magmatic settling came the idea of enrichment of the nickel ores by gravitative action. This mode of ore genesis has now been abandoned, and along with this has come the interpretation that the norite and the micropegmatite were separate and distinct intrusives.

The basin was interpreted first as a subsiding lopolith and later as a synclinally folded lopolith. But it has also been maintained that a basin of subsidence existed before the intrusion, and similarly that synclinal folding occurred before the intrusion. No agreement exists in regard to these hypotheses of placement. A recent highly speculative hypothesis by Wilson (1956) envisages the irruptive as the part of a funnel-shaped intrusive of which the bottom (concealed) consists of utrabasic rocks that underlie the norite. This seems to revert to the interpretation of magmatic differentiation by gravitative settling.

The micropegmatite consists generally of intergrowths of potash feldspar and quartz, arranged radially around plagioclase, commonly oligoclase. The mafic minerals are hornblende with less biotite, both much altered to epidote. The most siliceous part of the micropegmatite is not at its inner boundary on the east range, as earlier reported, but according to Knight (1923) near its basal part.

The norite has been studied petrographically by Phemister (1926), who concludes that this designation is a misnomer, because most of this intrusive contains little or no orthorhombic pyroxene. The common mafic mineral is hornblende, and though some of this is secondary, there is no evidence that it was derived from hypersthene. The plagioclase is a zoned labradorite, and some of the rock contains quartz. The so-called norite appears to lie petrographically between a monzotonalite and a granogabbro, and might be called a hornblende quartz gabbro. A more specialized designation would be bojite. The norite is most basic not at its base, but somewhere above its medial zone, close to the overlying transition zone.

The quartz diorite, to which reference has been made, occurs sporadically at or near the base of the norite, without clean-cut contacts between those two rocks, but with well-defined contacts with the members of the Mississagi quartzite and associated greenstone. It appears from subsurface exploration to disappear downward in the adjacent country rocks, and this is used by Hawley (1962, p. 26) as one line of evidence that the quartz diorite is merely a phase of the norite. The quartz diorite is composed of plagioclase (andesine to labradorite), quartz, pyroxene, amphibole, biotite, and accessory minerals, mainly apatite. The mafic minerals are in various stages of alteration—the pyroxene to hornblende and the amphibole to shreds of tremolite and actinolite. The biotite is bleached. As a whole, however, this rock is less altered than the norite near its basal contact.

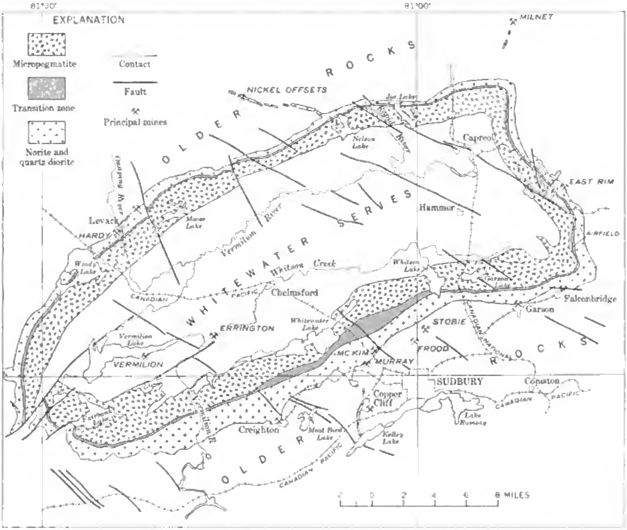

FIGURE 1.—Geologic map of "nickel irruptive," Sudbury district, Ontario. (Generalized from Geol. Soc. America, Toronto Field Trips Comm., 1953.)

ORE DEPOSITS

The nickel-copper ores occur along the north, south, and east ranges of the irruptive, but mainly along the south-southeast side. Most of the ore bodies are localized at two sites, one at or close to the basal contact of the norite with the underlying rocks and a second at distances up to 5 miles from the norite. These bodies are designated respectively as marginal and offset deposits. Some of the marginal deposits extend upward or laterally into the bounding norite, but very few lie entirely within the norite. The Falconbridge, Garson, Creighton, and Murray mines may be cited as examples of marginal deposits adjacent to norite, and the Levack mine as a marginal deposit that lies within but close to the base of the norite. The Copper Cliff, Worthington, and Frood-Stobie properties illustrate the offset lodes. A third type of deposit is represented by the Errington and Vermilion mines, where according to Thomson and others (1957, p. 85–86), the ore bodies are replacements of a chert-carbonate horizon that lies at the contact of the Onaping tuff and the overlying Onwatin slate.

A description of all the cited ore deposits and mines of the Sudbury district is obviously beyond the scope of this report; and only general relationships are warranted and offered. The ore bodies are generally irregular in outline, but where unfaulted are commonly lenticular with an orientation parallel to that of the norite, plunging therefore toward the center of the synclinal basin. Where faulting and minor folding occur, this general orientation may be reversed. The ores, according to Thomson and others (1957), lie

within a variety of host-rocks, which include quartzite, greenstone, quartz diorite, gabbro, norite, granite, andesite, and breccias of these rocks. The principal structures which have been provided channelways for the ore solutions are faults, breccia zones, and less definite loci of shattering and brecciation. Regardless of the nature of the deposits and of the solutions that produced them, it is clear that the sulfide ores are secondary with regard to their present host rocks.

These deposits have been classified by Hawley (1962, p. 32–38) into five types, designated as disseminated, massive, immiscible-silicate-sulfide, breccia, and vein stringer ores, of which the breccia ores are the most important. The primary minerals of both marginal and offset deposits, according to Hawley (1962, p. 41–128), are pyrrhotite, pentlandite, chalcopyrite, and cubanite, and the minor ore minerals are magnetite, ilmenite and pyrite. The rarer ore minerals comprise gersdorffite, niccolite, maucherite, heazlewoodite, bornite, valleriite, sphalerite, stannite, violarite, marcasite, native gold, silver, bismuth, and copper, tetradymite, hessite, chalcocite, bismuthinite, nickelferous pyrite, parkerite, schapbachite, galena, molybdenite, tetrahedrite, smalltite, danaite, and hematite. The secondary supergene ore minerals include millerite, marcasite, limonite, chalcanthite, melanterite, morenosite, annabergite, and erythrite. The principal carriers of the platinum metals are pyrrhotite, pentlandite, and chalcopyrite, though these metals are known in smaller amounts in cubanite and pyrite and may also be present in some of the rarer ore minerals. The platinum-bearing minerals, intergrown with or included in the ore carriers, include sperrylite, michenerite, froodite, and an unnamed palladium bismuthide, but work is in progress that undoubtedly will result in the discovery of other platinum and palladium minerals. The platinum metals also exist as molecular replacements within the cited carrier minerals. No native platinum metals or alloys exist in these ores.

The ores at the Errington and Vermilion mines are quite different from those of the marginal and offset deposits. The ore minerals at the Errington mine, according to Thomson and others (1957, p. 85), consist of fine-grained pyrite, sphalerite, chalcopyrite, pyrrhotite, and galena in a carbonate matrix; and the metallic products are zinc, lead, and copper, with small amounts of gold and silver and mere traces of nickel. The ore deposit and minerals of the Vermilion mine are generally similar, though the geologic environment is much more complex; but this deposit, where sperrylite was first discovered, had a high tenor in gold and platinum.

The gensis of the Sudbury deposits has not been settled, but three principal hypotheses have been formulated.

1. The ores are magmatic sulfides that originated in the norite and were segregated petrographically or gravitatively at the base of the irruptive, whence they were distributed along the contact and in zones of fracturing.
2. The ores resulted from the injection of a magmatic sulfide melt along channelways in the norite and adjacent country rock, after the solidification or partial solidification of the norite. The ore deposits resulting from these magmatic injections are designated by Hawley (1962, p. 148–150) as primary ores, because they are considered to be of magmatic origin, but in relation to their host rocks, such deposits are secondary and nonsyngenetic.
3. The ores are epigenetic and probably hydrothermal, resulting from the introduction of sulfides into the norite and adjacent country rock. The ore-bearing solutions may have come from norite, quartz diorite, or from deep-seated sources of unknown origin.

Knight (1923) has studied the norite throughout its thickness of 8,300 feet on the eastern nickel range and has found that the most basic part of the norite is not along its eastern edge but from 1,500 to 2,000 feet higher in the sequence. Also the most silicic part of the micropegmatite is not along its western edge but from 3,400 to 4,300 feet lower in the sequence. And finally, the country rock adjacent to the ore deposits may contain as much or more sulfides than the bounding norite. Hence, the first hypothesis no longer appears to be acceptable. The second hypothesis has been favored by many of the earlier writers and by Hawley in 1962. But the secondary nature of the sulfide ores and other lines of collateral evidence have led Dickson (1905), Knight (1917, 1920, 1923), Wandke and Hoffman (1924), Phemister (1926, 1937, 1956), Lockhead (1955), and other geologists to believe that the marginal and offset ore deposits are of epigenetic and hydrothermal origin. Thompson (1960) stated his belief that not only all the massive sulfides of the Sudbury district, but also the disseminated ores associated with them are of hydrothermal origin. The opinion is based upon the following criteria:

1. Spatial relationship of sulfide bodies to secondary structures, such as faults, folds, and fractures.
2. Wallrock alteration.
3. Well-defined paragenetic sequences of mineralization.
4. Different generations of sulfides.

5. Considerable variations in sulfide and metal content throughout the mineralized zones.
6. Irregular shape of mineralized bodies.

PLATINUM METALS

The tenors of all metals in the Sudbury ores are known to be variable, and maximum and minimum values for different mines are not commonly published. According to several authorities quoted by Hawley (1962, p. 116), the Ni:Cu ratio ranges from 1:0.5 to 1:3, but for the total production of the period 1947–57, this ratio was 1:0.8. The ratios pyrrhotite:chalcopyrite: pentlandite are estimated to be approximately 70:15:15.

The tenors of the platinum metals, which depend upon the absolute and relative amounts of the sulfides, are correspondingly indefinite. In ores that contained 5 percent nickel and copper, O'Neill and Gunning (1934, p. 66), have shown a mean tenor for the period 1912–15 of 0.014 ounce platinum metals per ton. Allen (1961, p. 138) states that the average value is 0.02 ounce per ton. Hawley (1962, p. 122) presents a mean tenor of 0.019 to 0.026 ounce per ton—a value taken from a statement by the Ontario Department of Mines, based upon the recovery of platinum metals from the Sudbury ores for the period 1947–57.

The nickel-copper ores at the different mines in the Sudbury district have different tenors in the platinum metals, so that the output of the platinum metals is not necessarily related to the output of the base metals. Thus by mining ores of higher or lower content of platinum, the output of the platinum metals may be increased or decreased without altering materially the production of nickel and copper. It is generally known that the tenor of platinum metals is higher in the offset deposits than in the marginal deposits.

The relative amounts of the different platinum metals in the Sudbury ores is also indefinite, but the production of these metals over a long period of years gives an average ratio for platinum and palladium and some data on iridium, ruthenium, and rhodium. Among the available estimates are those by Rogers and Young (1929) for the period 1923–27, O'Neill and Gunning (1934) for the period 1923–32, corrected to apply only to the Sudbury ores, Tremblay (1946) for the period 1937–41, and Hawley (1962) for the period 1947–57. These are presented in table 11.

TABLE 11.—*Platinum metals in percent, in platinum minerals, Sudbury district*

	Platinum	Palladium	Others
Rogers and Young (1929)	49. 02	48. 97	2. 01
O'Neill and Gunning (1934)	47. 99	45. 42	6. 59
Tremblay (1946)	54. 26	41. 65	4. 09
Hawley (1962)	46. 00	41. 00	13. 00

The indefinite character of these percentages is emphasized by another set of figures, quoted by Hawley (1962, p. 122) that apply to the mines of the Falconbridge Nickel Mines, Ltd. These, in percentages, are platinum 36.6, iridium 4.7, ruthenium 9.9, rhodium 8.8, and palladium 40.0. Here the ratio of platinum to palladium is approximately 1:1.1, which is the reverse of the four tenors shown above.

For recent years, much confidence should be placed on Hawley's estimate, which is based on productive data over a period of 10 years. Independent figures obtained by the writer from the U.S. Munitions Board and the War Production Board during World War II indicate that in general the amount of platinum exceeds that of palladium by 3 to 5 percent and that rhodium had the highest tenor of the minor elements, ranging from 8 to 12 percent. The tenor of ruthenium ranged from 2 to 3 percent and that of iridium from 1 to 2 percent. Osmium is rarely mentioned as one of the recovered elements, because it probably is lost by sublimation during smelting.

The amounts of the precious metals in the ores of the Falconbridge mine are well shown in a paper by Lewis (1957), wherein are given the results of numerous chemical analyses of crude ores, pyrrhotite concentrates, and flotation concentrates. Neglecting the gold and silver in these determinations and recomputing to 100 percent, the mean tenors of the platinum metals are shown in table 12.

TABLE 12.—*Platinum metals, in percent, in ores from Falconbridge mine, Sudbury district*

	Platinum	Rhodium	Palladium
Crude ores	54. 1	14. 2	31. 7
Pyrrhotite concentrates	38. 5	29. 5	32. 0
Flotation concentrates	54. 5	8. 3	37. 2

The percentages of platinum and palladium in the flotation concentrates agree fairly well with those heretofore presented and confirm the prevalence of platinum over palladium. The percentage of rhodium in the flotation concentrates agrees with the independent figures cited on page 24. The high percentage of rhodium in the pyrrhotite concentrates suggests a possible concentration of this metal in pyrrhotite; in any event it emphasizes the differences of tenors in different host minerals.

Spectrographic data have been presented by Hawley, Lewis, and Wark (1951, p. 158) on the tenors of the platinum metals in the ore minerals pyrrhotite, chal-

copyrite, pentlandite, and pyrite, together with tenors from the mixed arsenides maucherite, niccolite, and gersdorffite. These are shown in table 13.

TABLE 13.—*Spectrographic data, in ounces per ton, on platinum and palladium in ore minerals, Sudbury district*

	Platinum	Palladium	Both
Pyrrhotite	0. 148	0. 472	0. 620
Chalcopyrite	. 078	. 735	. 813
Pentlandite	. 935	. 440	1. 375
Pyrite	. 011	. 009	. 020
Maucherite	Tr.	7. 223	7. 223

More complete spectrographic data, however, have recently been published by Hawley (1962, p. 124–125). These are of particular interest in that they differentiate between the average run of ores and the ores from an offset deposit. Noteworthy are the higher tenors in platinum metals from an offset deposits. Changed slightly, so that platinum, rhodium, and palladium sum to 100 percent, these data are presented in tables 14 and 15.

TABLE 14.—*Mean tenors of platinum metals, in percent, in common ore minerals, Sudbury district*

	Pt	Rh	Pd	Total metals (ounces per ton)
Pyrrhotite (mean of 37 samples)	57. 2	11. 1	31. 7	0. 035
Chalcopyrite (mean of 7 samples)	17. 7	. 9	81. 4	. 224
Pentlandite (mean of 3 samples)	33. 0	7. 5	59. 5	. 158
Pyrite (mean of 3 samples)	56. 2	2. 5	41. 3	. 055

TABLE 15.—*Mean tenors of platinum metals, in percent, in minerals of an offset deposit, Sudbury district*

	Pt	Rh	Pd	Total metals (ounces per ton)
Pyrrhotite	44. 3	7. 0	48. 7	0. 055
Chalcocopyrite	28. 3	. 2	71. 5	. 235
Pentlandite	25. 1	10. 3	64. 6	. 307
Pyrite	50. 3	7. 5	42. 2	. 137
Mill average, 6 months	31. 7	4. 8	63. 5	. 155

Tables 13–15 do not entirely agree with one another, but table 15, because the data are more complete, affords a means of evaluating the relative amounts of platinum, rhodium, and palladium in pyrrhotite, chalcopyrite, and pentlandite. To accomplish this, the amounts of the three platinum metals are recomputed to ounces, neglecting the small amounts present in pyrite. But according to Hawley (1962), the mean ratios of pyrrhotite, chalcopyrite and pentlandite in the ores are respectively 70:15:15. Therefore, weighting the ounces of platinum metals respectively in pyrrhotite, chalcopyrite, and pentlandite are shown in table 16.

TABLE 16.—*Contents, in percent, of platinum, rhodium, and palladium in the principal ore minerals of marginal deposits, Sudbury district*

	Platinum	Rhodium	Palladium
Pyrrhotite	50. 44	56. 67	65. 20
Chalcopyrite	21. 41	6. 30	22. 96
Pentlandite	28. 15	37. 03	11. 84

Pyrrhotite is clearly the principal carrier of the platinum metals, and chalcopyrite is the smallest, carrying little rhodium and less palladium. Pentlandite, according to these figures, contains comparable amounts of platinum and rhodium but less palladium. Analyzing similarly the figures of table 15, and neglecting as before the content of platinum metals in pyrite, the data shown in table 17 are derived.

TABLE 17.—*Contents, in percent, of platinum, rhodium, and palladium in the principal minerals of an offset deposit, Sudbury district*

	Platinum	Rhodium	Palladium
Pyrrhotite	44. 20	35. 89	25. 49
Chalcopyrite	25. 84	. 94	34. 19
Pentlandite	19. 96	63. 17	40. 35

These two sets of data indicate that the pyrrhotite of the offset deposit contains less platinum, less rhodium, and much less palladium than the pyrrhotite of the marginal deposits. The chalcopyrite of the offset deposit contains a little more platinum, very much less rhodium, and more palladium than the chalcopyrite of the marginal deposits. And the pentlandite of the offset deposit contains less platinum, much more rhodium, and much more palladium than the pentlandite of the marginal deposit. This analysis, however, refers to relative proportions of the platinum metals in the three ore-bearing minerals, and does not at all vitiate the conclusion that the total amount of the platinum metals in the offset deposits exceeds that of the marginal deposits.

Sperrylite, the diarsenide of platinum, is known to be present in most, if not all, of the nickel-copper ores, and it has been assumed to be the main source of platinum in the Sudbury district. But no quantitative data in favor of this interpretation have been presented, and in recent years this hypothesis has been questioned, notably by Lewis (1957, p. 1–5). In a letter (Oct. 18, 1960) to the writer, Mr. Lewis states: "In the examination of some hundreds of polished

sections of Sudbury ore minerals, I have rarely seen sperrylite. On the other hand, almost any sample of pyrrhotite, pentlandite, or chalcopyrite, when treated by fire assay, with a spectrographic analysis of the resulting bead, will show evidence of the presence of platinum metals." He therefore believes that sperrylite is not a major source of the platinum metals, but instead that they occur mainly as very dilute solid solutions in the major ore minerals, probably as substitutions in the crystal lattices.

The recent discoveries, however, of new platinum minerals by Hawley and Berry, Genkin and collaborators, Stumpfl, Borovskii, and others suggest strongly that numerous platinum minerals exist as discrete intergrowths in the sulfide ores. In general, therefore, the present state of knowledge indicates that in deposits of the Sudbury type, the platinum metals occur mainly in pyrrhotite, chalcopyrite, and pentlandite, both as minute included minerals but also as molecular replacements. The proportions of total and individual platinum metals derived from these two sources have not been determined.

OTHER LODES

Production was begun in 1962 at another platinum bearing lode at Gordon Lake, 55 miles north of Kenora, in the Kenora mining division, southwestern Ontario. This is the property of the Nickel Mining and Smelting Corp., Ltd. About 3 million tons of ore have been proven to the 1,000-foot level, but one shaft was sunk in 1962 to a depth of 1,817 feet, and other reserves will be established. The output is about 500 tons of ore daily. The nickel-copper concentrates are shipped first to Lac du Bonnet, Manitoba, and thence to Copper Cliff for smelting.

This ore deposit has been described by Thomson and others (1957). The ore which dips steeply north and lies in an east-west fault zone, is bounded on the north by gneiss and on the south by massive granite. Along the fault zone are irregular bodies of chromite-bearing peridotite, which intrude the gneiss. These lenses of peridotite and the adjacent gneiss are mineralized by disseminated and massive pyrrhotite, pentlandite, and chalcopyrite. Joints in the peridotite and banding in the gneiss appear to control the placement of the ores. The tenors in nickel and copper are respectively 1.24 and 0.69 percent, and the gold and platinum metals add to 0.02 ounce per ton. The U.S. Bureau of Mines, however, reports the tenor in platinum metals to be about \$3 (Canadian) per ton of ore.

The Alexo mine is in east-central Ontario, about 3½ miles southeast of Kelso, and more than 100 miles northeast of the nearest point on the north range of the Sudbury basin. This property, when owned by the Mond Nickel Co., was operated from 1912 to 1920, with a total production of about 51,860 tons of ore having a tenor of 4.2 percent nickel and 0.5 percent copper. The tenor in platinum metals was reported to be about 0.03 ounce per ton of ore. The property is now owned by the International Nickel Co. of Canada, Ltd., but has not been operated in recent years.

A cross section of the west drift of this mine, as given by Baker (1917), shows that the ore body where it was worked had a thickness of 10 to 12 feet and plunged steeply northwestward. It is bounded on the northwest side by serpentinite and on the southeast side by pillow lava. The ore body is known to have a length of 700 feet and to extend to a minimum depth of 350 feet below the surface. Sulfides are disseminated in the adjacent serpentinite, but the workable ore consists of massive sulfides, mainly pyrrhotite and pentlandite, with small amounts of chalcopyrite and pyrite.

Platinum metals have been recorded by O'Neill and Gunning (1934, p. 56–57 and 71–72) at five other sites in Ontario. These and six additional sites, taken from Thomson and others (1957), are listed below.

1. Shebandowan nickel-copper property, at Southwest Bay, lower Shebandowan Lake, Thunder Bay district, southwestern Ontario, about 73 miles west of Port Arthur. This property is now owned by the International Nickel Co. of Canada, Ltd.
2. Detroit-Algoma, mine, McTavish township, Thunder Bay district, southwestern Ontario.
3. Lode in Eby township, Timiskaming district, north of Sudbury.
4. Lode in Reaume township, Timiskaming district, north of Sudbury.
5. Cuniptau lode, in Strathy township, 4 miles northwest of Timagami and 60 miles northeast of Sudbury. Formerly owned by Ontario Nickel Corp., Ltd., now listed as property of Trebor Mines, Ltd.
6. Almo Lake, 4 miles west of Gordon Lake and 53 miles north of Kenora, Kenora Mining division, southwestern Ontario. Owner, Norpax Oils and Mines, Ltd.
7. Lode in Pardee township, about 50 miles southwest of Port Arthur, Port Arthur mining division, southwestern Ontario. Owner, Mattawin Gold Mines, Ltd.
8. Lode in Rathbun township, Sudbury mining division. Owner, Dolmac Mines, Ltd.
9. Milnet mine, Parkin township, Sudbury mining division. Property of Jonsmith Mines, Ltd.

10. Nickel Offsets mine, Foy township, Sudbury district, property of Nickel Offsets, Ltd.
11. Quinn claim, Munro township, Ontario.

MANITOBA

A number of lodes, mainly of nickel-copper and copper-zinc ores, are known in Manitoba, and some of these have become significant producers of the base metals, though most of them contain no platinum metals. The most important of these lodes, which is platinum bearing, is in the Thompson district of north-central Manitoba, between two forks of the Nelson River and about 390 miles north of Winnipeg. The newly built town of Thompson, where the Thompson mine is located, is about 2 miles south of Burntwood River, a tributary of the North Fork of Nelson River, and is connected southeastward by a 30-mile spur to the Canadian National Railroad. The discovery and development of this mine are well described in a magazine supplement of the "Northern Miner," dated August 17, 1961. The geology and ore deposits were described briefly by Davis (1960) and more fully by Zurbrigg (1962).

Zurbrigg has outlined a rectangular area trending northeast, with a length of 85 miles and a width of 15 miles, which includes the more important nickel-copper ore deposits. These, named from northeast to southwest, are the properties at Moak Lake, Mystery Lake, Thompson, Pipe Lake, Hambone Lake, Grass River, and Soab Lake. The mineralization, however, extends northeastward to Ospwagan Lake and southwestward to Setting Lake, for a total distance of about 200 miles. The International Nickel Co., of Canada, Ltd., beginning in 1948, prospected this area thoroughly and made the first discovery at Moak Lake in 1952; the deposit at Thompson was found in 1956. Two shafts were sunk on the Thompson deposit, of which the principal working shaft reached initially a depth of 2,000 feet, with operating drifts on the 200-foot levels; but this shaft was sunk to a lower level in 1964. A third operating shaft was completed in 1966 to a depth of 2,400 feet. The mill that was built to handle these ores has a daily capacity of 6,000 tons of ore, but is operated at 4,500 tons a day, yields annually 75 million pounds of refined nickel. The nickel refining plant at Thompson is the second largest in the world. Three new mines being developed at Soab Lake, Birchtree, and Pipe Lake are scheduled to come into production in 1967. This mining is being done by the Canadian Nickel Co., Ltd., a subsidiary of the International Nickel Co. of Canada, Ltd. In 1962, the Thompson mine had 1,800 employees who live at Thompson, which has a population of 4,500 people. Electric power is drawn from the Kelsey hydroelectric generating station on Nelson River, about 53 miles from Thompson.

The ore reserves at the Thompson mine are estimated at 25 million tons, with a tenor of 2.8 percent nickel and 0.2 percent copper. The amount of palladium in these ores is comparable with that recovered at Sudbury, but the content of platinum and the minor platinum elements is lower. Besides the platinum metals, there are other byproducts of cobalt and sulfur. The deposit at Moak Lake probably contains ore reserves twice as great as those at the Thompson mine, but the content of nickel is only about 0.7 percent. The total reserves for the entire mineralized area are believed by Allen (1960) to be about 200 million tons and by the Northern Miner (1961) to be perhaps as much as 500 million tons.

The nickel ores of the Thompson-Mystery Lake-Moak Lake area are stated by Wilson and Brisbin (1961) to be localized within an intensely deformed gneissic zone that lies between two great blocks of Precambrian rocks, of which the older lies to the southeast and the younger to the northwest, though both strike generally eastward. The older block consists dominantly of greenstone with less graywacke; the younger comprises limestone, quartzite, and conglomerate with a minor volume of lavas. The intermediate zone consists dominantly of gray and pink biotite gneiss which trends northeastward and is characterized by major thrust faulting along its length. This gneiss is believed to have been intruded as a granite into the sedimentary rocks and thereafter to have been greatly metamorphosed. Numerous other igneous rocks, mainly of intrusive character, occur within the gneissic zone; these include diorite, diabase, gabbro, and various peridotites, of which some are strongly serpentinized

The metasediments include quartzite, subgraywacke, limestone, skarn, an iron-formation, biotite schist, amphibolite, and minor amounts of greenstone. The peridotites are linearly arranged in zones parallel to the sheared metasediments and volcanics. The nickel deposits occur as massive ore bodies and stringers in schist, metasediments, and gneiss, and as disseminations and stringers in serpentinized peridotite.

The nickel-copper ores of this district exist in two distinct environments. At the outset of exploration, these deposits were thought by geologists to consist of disseminated ores in the included and bounding peridotites, as at Moak Lake. Later, however, deposits of higher grade were found in the metasediments of the mineralized zone of faulting, and these are represented by the ore deposit of the Thompson mine. This deposit may be described as a sheet of sulfide breccia,

10 to 75 feet wide, which lies mainly in biotite schist and extends for a distance of 3½ miles. Only a very small part of the ore breccia lies in peridotite. The structure controlling the ore is an anticlinal fold, and the locus of the ore is a zone of schist which is continuous over the length of the anticline. The greatest concentration of ore is along the east limb of the south-plunging anticline, along its nose, and in minor crenulations.

The ore consists mainly of pyrrhotite, pentlandite, and pyrite, with less chalcopyrite and marcasite and traces of nickel arsenides. The sulfides occur as fine-grained masses, lenses, and veinlets in brecciated schist and as stringers, veinlets, and disseminations in adjacent peridotite. Both the coarse and the fine-grained ores are termed "sulfide breccia," as many inclusions and remnants of country rock are included in the ore.

The other type of deposit is exemplified by the low-grade ores at Moak Lake, Mystery Lake, Pipe Lake, Soab Lake, and at other localities within the mineralized zone. Such ores consist of disseminated pyrrhotite and pentlandite in intrusive bodies of serpentinite, and are reported to have tenors in nickel ranging from 0.45 to 0.75 percent. These deposits are characterized by low tenors in chalcopyrite and therefore in copper. All these deposits are in varying degrees platinum bearing.

A copper-nickel deposit, owned by the Sherritt-Gordon Mines, Ltd., is on Lynn Lake, about 145 miles northwest of Thompson. This property is reported to have reserves of 13,820,000 tons of ore, and it was brought into production in 1953. The ore consists of pyrrhotite, pentlandite, chalcopyrite, and pyrite, which occur both in stockworks and in disseminated form. Small amounts of cobalt, zinc, gold, and platinum metals are also present. At the outset, the platinum metals were not recovered, because the chemical-leach method used in treating the concentrates was incapable of saving them. Improvements in milling practice, however, have resulted in a small output of platinum metals.

An area of some interest where platinum metals are present has been recorded by Wright (1932). This is in the Oiseau (Bird)-Maskwa Rivers area, in southeastern Manitoba, where several copper-nickel replacement deposits occur in Precambrian rocks. The principal country rock comprises steeply folded andesitic lavas and quartzose tuffs which are intruded by dikes and stocks of peridotite and gabbro, as well as granitic rocks. The ores are copper-nickel replacement deposits which are localized in sheared zones in volcanic rocks close to and in part within marginal parts of the basic and ultrabasic rocks. The principal ore minerals are pentlandite, nickeliferous pyrrhotite, chalcopyrite, and cubanite. At the Hititrite mine, in the Maskwa River area, the tenor of platinum metals was found to be 0.02 percent.

Another area recorded by Uglow (1919) is near The Pas, in western Manitoba, about 75 miles south-southeast of Flin Flon. Here, in the shaft of the Northern Manitoba and Development Co., platinum was found in a gold-quartz vein, with a tenor alleged to have been $17 a ton. Another locality mentioned by O'Neill and Gunning (1934) is in the Star Lake district, in southeastern Manitoba. The deposit near The Pas is another occurrence of platinum in a quartz vein, in which gold occurs in pyrite and arsenopyrite; the tenor of platinum was determined to be 0.10 ounce per ton of ore.

QUEBEC

A nickel-copper ore deposit has recently been discovered in a Motte township, adjacent to Malartic, in southwestern Quebec. Operated by the Marbridge Mines, Ltd., this property is owned jointly by Falconbridge Nickel Mines, Ltd., and the Marchant Mining Co. Drilling has been done to a depth of 1,200 feet, and ore has been developed from a shaft at the 750-, 900-, and 1,050-foot levels. Production was begun in 1962, with a daily output of 400 tons of ore, from which 2,500 tons of concentrates is produced monthly. These are smelted at Falconbridge. The tenor in nickel is 2.11 percent. The ore is platinum bearing, but the tenor in platinum metals has not been announced.

Another ore deposit containing nickel and copper has been found in the Belleterre district, Guillet township, of southwestern Quebec. This property is being developed by the Lorraine Mining Co., but 80 percent of the stock is owned by the McIntyre-Porcupine Mines, Ltd. Drilling indicates ore reserves of 550,000 tons, and mining was planned to begin in 1965. The tenor in nickel is about 2.1 percent, and the tenor in platinum metals is reported to be about 0.05 ounce per ton of ore.

Traces of platinum metals have also been reported by O'Neill and Gunning (1934, p. 55) in chromite ore from St. Cyr, Quebec.

NORTHWEST TERRITORIES

A platinum-bearing nickel-copper lode, originally called the Rankin Inlet deposit was discovered in 1928 at the top of a small peninsula, about 7 miles west of Falstaff Island. The literature has numerous references to this deposit, but the ones which form the basis of this description are principally those by Weeks (1932),

Drybrough (1932), O'Neill and Gunning (1934), the Imperial Institute (1936), Pelzer (1950), the U.S. Bureau of Mines Mineral Trade Notes (1961), and miscellaneous notes in Canadian and United States mining journals.

The Rankin Inlet lode was prospected intermittently for nearly 30 years before production began in 1957. The property produced 460,000 tons of ore up to the time when operations ceased in 1962. The mean tenors of nickel and copper, according to the U.S. Bureau of Mines Mineral Trade Notes (1961, v. 53, p. 41), were 3.47 and 0.99 percents; and from other sources the tenors of platinum and palladium are known to have been respectively 0.03 ounce platinum and 0.06 ounce palladium per ton of ore. The platinum metals were not recovered.

The local geologic features comprise a lenticular sill of serpentinized pyroxenite, from 200 to 300 feet thick, which lies between a sequence of overlying "upper volcanics" and an underlying sequence of Precambrian sedimentary rocks. The ore is localized in the basal part of the pyroxenite and is interpreted as magmatic ore that resulted from a splitting of the magma into rock-forming and ore-mineral fractions before its cooling and crystallization. The ore minerals that have been identified, named in the order of their abundance, are pyrrhotite, pentlandite, chalcopyrite, magnetite, pyrite, violarite, marcasite, and gersdorffite. The platinum metals are included mainly in pentlandite and pyrrhotite and in smaller amounts in chalcopyrite.

Another lode of a similar type has been found at Ferguson Lake, about 150 miles west of Rankin Inlet. Much drilling has been done at this property, but the results of this work are not known to the writer.

A lode in which the platinum metals occur in a vein of quartz and pyrite was found by Wait (1910) in a sample collected from the northern part of Baffin Island on Strathcona Sound, an arm of Admiralty Island.

A large layered basic pluton has recently been discovered in the Copper-mine area, in the northern part of Northwest Territories, and has been described by Smith and Kapp (1962). This mass, known as the Muskox intrusion, is dikelike in plan and funnel-shaped in cross section. It has four principal units which include a feeder, marginal zones, a central-layered series, and an upper border group. The overall length is 74 miles, of which 37 miles represents the feeder, which contains bronzite gabbro and picrite in zones parallel to a nearly vertical axis. The thickness of the feeder ranges from 500 to 1,800 feet. The marginal zones are parellel to the walls of the intrusion, which dip inward at an angle of 23° to 57°; these zones grade from bronzite gabbro at the contact through picrite and feldspathic peridotite to peridotite and in places dunite. The marginal zones range in thickness from 200 to 1,200 feet. The central zone is 8,500 feet thick and is known to consist of 38 principal layers of dunite, peridotite, pyroxenite, and gabbro. These layers are nearly horizontal and are discordant to the marginal zones. The upper zone, which is 200 feet thick, shows an upward gradation from gabbro to granophyre.

Nickel-copper ores occur along the walls of the intrusion, and within one horizon of pyroxenite are ores containing disseminated chromite, copper-nickel sulfides, and platinum metals. A marked resemblance exists between this ore body and the Merensky zone of the Transvaal, and its great size suggest that another important copper-nickel-platinum deposit of the Sudbury type may have been discovered.

BRITISH COLUMBIA

LODES

A platinum-bearing nickel-copper lode, owned by the Pacific Nickel Mines, is about 75 miles east of Vancouver and 7 miles northeast of Hope. The principal habitat of the ore is stated by Aho (1956), to be a stocklike body of pyroxenite that has a visible diameter of about 1½ miles and that has cores of peridotite and hornblendite. This mass appears to cut an adjacent diorite, but is itself cut by dioritic dikes—a fact suggesting approximate contemporaneity. The ore bodies are elongate, steeply pitching, parsnip-shaped structures consisting in part of sulfides with olivine-rich ores and in part of massive sulfide-silicate bodies. The principal ore minerals are disseminated and massive pyrrhotite with subordinate amounts of pentlandite and chalcopyrite. The ore has an average tenor of 1.4 percent nickel, 0.5 percent copper, and 0.01 ounce platinum metals per ton. The sulfides are considered to be of hydrothermal origin.

A score of platinum-bearing lodes in British Columbia are mentioned by O'Neill and Gunning (1934), but none of these have been mined, or appear to have much chance of being developed. The more important ones, which include several occurrences of the platinum metals in siliceous gangue minerals, are summarized briefly below. Both Uglow (1919) and Vogt (1927) have listed the principal lodes in which platinum occurs in this environment. The list by O'Neill and Gunning follows:

1. Swede group of claims outside Lockeport Harbour, east side of Moresby Island, about 120 miles south-southwest of Prince Rupert. The lode is an immense deposit of low-grade copper ore, consisting

of small veinlets and disseminations of chalcopyrite and bornite in diabase. A sample of the bornite assayed 0.01 ounce platinum and a trace of palladium to the ton.

2. Scottie Creek, about 140 miles north-northeast of Vancouver. The lode is a deposit consisting of disseminations, nodules, and lenses of chromite in serpentinite derived from an ultrabasic intrusive. Two assays of the chromite showed 0.02 and 0.10 ounce of platinum to the ton.
3. Mount Ida, about 50 miles east of Kamloops. The platinum occurs in quartz veins and in quartz stringers that lie in a wide shear zone and that contain copper, lead, and zinc sulfides. Assay show values ranging from 0.02 to 0.03 ounce platinum metals to the ton.
4. The Tulameen placer district, described on pages 29–31. The platinum-bearing streams head in areas of peridotite and pyroxenite. According to O'Neill and Gunning, platinum has been reported to occur in serpentinite dikes, masses of chromite, in replacement and vein deposits, in sulfides in greenstone, and in sheared and altered granodiorite. Assays ranged from 0.1 to 4.0 ounces per ton of ore.
5. Mother Lode claim, Burnt Basin, about 3 miles west of Coryell. The country rock consists of basic eruptive rocks, largely altered to serpentinite as in the Tulameen placer area. Platinum occurs with chalcopyrite, pyrite, galena, sphalerite, and molybdenite in gold-bearing quartz veins between two porphyry dikes. Assays show tenors in platinum metals ranging from 0.06 to 0.10 ounce per ton.
6. Nickel Plate mine, at Hedley. Platinum is reported to occur with auriferous arsenopyrite in metamorphosed limestone. One assay indicates a tenor of 0.5 percent platinum, which was thought to be present as sperrylite.
7. The old Sappho property, close to the international boundary between British Columbia and Washington and about 2½ miles east of Midway. The country rock is argillite intruded by diorite, pyroxenite, and alkali-syenite dikes. Chalcopyrite close to the pyroxenite assayed 0.03 ounce platinum to the ton of ore.
8. Maple Leaf and several other properties in the Franklin Mining camp, about 135 miles east-northeast of Hope. A contact metamorphic deposit, called "The black lead," occurs in impure quartzite and greenstone, near the contact with a shonkinite, which is a marginal phase of an augite-syenite intrusive. The principal ore minerals are chalcopyrite, pyrite, a little bornite, and the accessory minerals apatite and sphene. Numerous assays show tenors in the platinum minerals ranging from 0.007 to 0.26 ounce per ton of ore.
9. Properties in the vicinity of Cascade, near the international boundary line, a few miles south of the Mother Lode claim. One of these is a chromite, deposit in serpentinized dunite, which contains platinum metals from traces up to 0.15 ounce per ton of ore.
10. Sullivan mine, about 60 miles east-northeast of Nelson. Palladium and a little platinum are recovered commercially from the lead-zinc ores of this property.
11. Cable claim and vicinity of Nome claim, in Ainsworth mining division. The ore at the Cable claim is auriferous pyrite in a quartz vein, with a tenor in platinum of 0.07 ounce per ton. The ore near the Nome claim came from a slide on Kaslo River, and the platiniferous rock, which resembles feldspathic quartzite, is reported to have assayed 0.05 to 0.08 ounce platinum to the ton of ore.

PLACERS

The placers of British Columbia lie in the many tributary valleys of the Columbia, Frazer, Peace, and Liard Rivers, but the belt continues northwestward into Yukon, and veers thence westward into interior Alaska.

Some of these Canadian gold placers also contained small amounts of the platinum metals which generally yielded no significant production. One area, however, known as the Tulameen district, had in earlier years an important output of the platinum metals; and because the geology of this area has genetic significance, it is briefly described in succeeding pages.

TULAMEEN DISTRICT

The Tulameen district, as mapped geologically by Camsell (1913) on a scale of 1:62,500, is an area of 13 miles square, with the southern boundary 31 miles north of the international boundary between Canada and the United States and the western boundary approximately at long 120°58′ W. A geologic map of a larger area, called the Princeton map area, was later prepared on a smaller scale by Rice (1947). The geography and geology of a part of the Tulameen district and some adjacent territory, taken from the maps by Camsell and Rice, are shown in figure 2. The platinum deposits of the Tulameen district are also described by O'Neill and Gunning (1934, p. 89–98).

The sedimentary country rock of this area consists principally of the Tulameen group of rocks, which are mainly andesitic flows and breccias, limestone, and

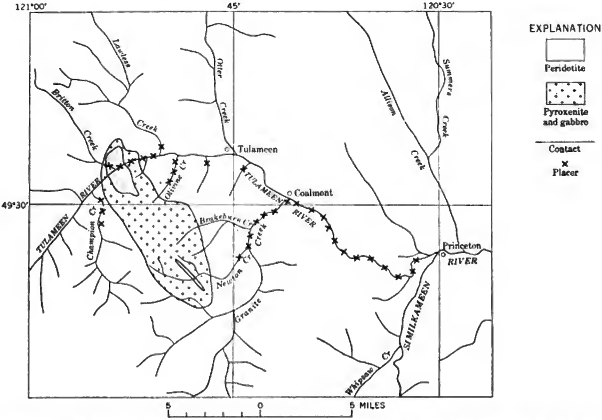

FIGURE 2.—Gold-platinum placer deposits, Tulameen Valley, British Columbia. (Generalized from Camsell, 1913, and Rice, 1947.)

argillite, of Triassic or Carboniferous age. There are five igneous formations, all of which are believed to be of Jurassic age; those which bear particularly on the origin of the platinum metals are two formations of ultrabasic rocks, which are shown in figure 2. Also present are Oligocene sedimentary and volcanic rocks, capped by olivine basalt. Intense glaciation of this area during the Pleistocene epoch produced U-shaped principal valleys and hanging tributary valleys. Most of the placers are therefore of postglacial age, though some that lie in protected valleys athwart the main movement of the ice may antedate Wisconsin time.

A large intrusive mass of pyroxenite and gabbro, with a length of 11 miles and a maximum width of 3½ miles is transected near its northwestern end by the Tulameen River and extends southeastward into the drainage of Granite Creek. A small body of peridotite occurs near the northwestern end of the pyroxenite and gabbro, and a dikelike body of peridotite is included near its southeastern limit. Some ultrabasic rocks are also reported in the upper valley of Lawless Creek.

All the streams that carry platinum metals in workable quantities head in ultrabasic rocks, or in areas closely adjacent thereto; and the peridotite is considered to be more important as a source rock than the pyroxenite and gabbro. The streams that have yielded platinum metals are Tulameen River and Granite Creek with its three northern tributaries called Brakeburn, Newton, and Badger Creeks; Olivine (Slate) Creek, Cedar and Hines Creeks, respectively east and west of Olivine Creek, and Champion Creek; and Lawless (Bear) and Britton (Eagle) Creeks, which are northern tributaries of Tulameen River. Gold and platinum have also been found along Similkameen River, from 30 miles above to 20 miles below Princeton, where they were doubtless transported in glacial deposits. The deposits downstream from Princeton were worked intermittently, but not very successfully.

The Tulameen River was generally productive from Princeton upstream to Coalmont, at the mouth of Granite Creek, a distance by stream of about 12 miles, though the deposits were not of very high grade. From Coalmont upstream to Olivine Creek, the deep glacial

gravels of Tulameen River have not been worked; but the stream and terrace gravels from Olivine Creek upstream to Champion Creek were found to constitute high-grade placers. The coarsest platinum on Tulameen River was also found within this stretch. The deep deposits downstream from Olivine Creek may sometime be dredged successfully.

The placers of Granite Creek, from the Tulameen River upstream to the mouth of Newton Creek, had the highest tenor in platinum metals of the district. Upstream from Newton Creek, the productive gravels are deeply buried under glacial deposits, and have not been successfully mined. Olivine Creek, for a distance of 4 miles from its mouth, also had high-grade gravel deposits.

Gold is almost everywhere more plentiful in these placers than the platinum metals. The gold-platinum ratio was found to be variable, depending on the locations of the placers, ranging from 4:1 in the lower Tulameen valley to 1:1 in the valley of Olivine Creek. A mean value of this ratio can be obtained from the gold production (in dollars) and the platinum production in ounces for the years 1887-1899, 1901-1902, and 1904-1905, as given by O'Neill and Gunning (1934, p. 95). Regarding the dollars of the table for these years as representative of the value of pure gold (not gold bullion), and taking the fineness of the placer gold as 935, the mean gold:platinum ratio for the district appears to be about 2:1.

The platinum metals occur as small, rounded, equidimensional grains, many of which are pitted as a result of the weathering out of other minerals; and some have adhering grains of chromite or magnetite. These grains, in the upper valley of Tulameen River and its tributaries, ranged in size from less than one millimeter to 4 millimeters, and the largest recorded nugget weighed half an ounce. A sample, recently obtained by the writer, came from a right limit terrace, about 1½ miles west of Princeton. This was found to have the following magnetic properties:

Ferromagnetic	32.9 percent
Paramagnetic	64.2 percent
Very weakly magnetic	2.9 percent

The heavy minerals recovered from the gold-platinum placers included magnetite, chromite, a little pyrite, and rarely native copper. The gold, judging from one assay given by O'Neill and Gunning (1934, p. 98) was of high grade, with a fineness of about 935.

The principal source of most of the platinum metals found in this area is the peridotite, though the chemical analyses recorded by Kemp (1902, p. 47-51) also indicate their presence in serpentinite, pyroxenite, and chromite. The platinum metals have also been reported in this district in other environments, at one place with pyrrhotite, chalcopyrite, pyrite, and sphalerite as a replacement deposit in limestone, at a second locality with copper sulfides in a greenstone dike, and at a third site in a shear zone in granodiorite.

No superior analyses of the platinum metals from the Tulameen district are available, but one inferior analysis was made by Hoffman (1888), and another is inferred from a record of production in 1930. The analysis by Hoffman is shown both with and without base metals, as A_1 and A_2. The production record is given as analysis B. These analyses are shown as table 18.

TABLE 18.—*Composition, in percent, of platinum metals, Tulameen district*

	A_1	A_2	B	Mean
Platinum	73. 20	83. 33	86. 09	84. 71
Iridium	1. 16	1. 32	2. 78	2. 05
Osmium plus iridium	10. 68	12. 16	10. 14	11. 15
Rhodium	2. 61	2. 97	. 60	1. 79
Palladium	. 19	. 22	. 39	. 30
Copper	3. 44			
Iron	8. 72			
Total	100. 00	100. 00	100. 00	100. 0

These two analyses are in general agreement in their tenors of platinum, and in the combined tenors of osmium plus iridium. Referring to table 37 of this report, it will be seen that the mean value of platinum in table 18 is quite similar to that recovered in the Goodnews Bay district, Alaska, and if the mean value of iridium is added to that of osmium and iridium, it appears that the sum of these two metals is also comparable with that of the Alaskan product.

The total output of platinum metals from the Tulameen district is not accurately known. According to Camsell (1913, p. 143), the production for 17 years in the period 1885–1909 was 9,860 fine ounces, but the output has not been recorded for the period 1910–32, after which mining practically ended. According to Quiring (1962, p. 93), the production of placer platinum from Canada for the period 1876–1930 amounted to about 18,775 troy ounces, most of which came from the Tulameen placers. There was a maximum production of 2,120 ounces in 1891. Poitevin in (1924) and O'Neill and Gunning (1934) agree that if proper records had been kept, the total production from the beginning to the end of mining should be approximately 20,000 ounces.

OTHER PLACERS

Numerous other gold placers in British Columbia are known to contain small amounts of platinum metals, but none of these has yielded any significant production. O'Neill and Gunning (1934, p. 76–89 and 98–102) have described these deposits and have published sketch maps showing their locations in British Columbia. They also have given what is known of the gold and platinum tenors of the gravels. It suffices here merely to tabulate the known localities, as follows.

Localities of platinum-bearing placers in British Columbia

1. Thibert Creek, a tributary of Dease River, Liard mining division.
2. Ruby Creek, Atlin mining division.
3. Graham Island, Queen Charlotte mining division.
4. Finlay River and tributaries, Omineca mining division.
5. Parsnip River and tributaries, Omineca mining division.
6. Dog Creek, a tributary of Stuart River, Omineca mining division.
7. Peace River, Peace River mining division.
8. Fraser River and tributaries, Quesnel mining division.
9. Government Creek, an eastern tributary of Fraser River, Cariboo mining division.
10. Quesnel River and tributaries, Quesnel mining division.
11. Bonaparte River and tributaries, Clinton mining division.
12. Tranquille River and tributaries, Kamloops mining division.
13. North Thompson River and tributaries, Kamloops mining division.
14. Deadman River and tributaries, Ashcroft mining division.
15. Coquihalla River and tributaries, Yale mining division.
16. Similkameen River and tributaries, Similkameen mining division. The Tulameen district lies in the drainage basin of Similkameen River.
17. Kettle River and tributaries, Greenwood mining division.
18. Okanagan River and tributaries, Osoyoos mining division.
19. Lardeau River and tributaries, Lardeau mining division.
20. Tributaries of Columbia River, Revelstoke mining division.
21. Tributary of Jervis Inlet, Vancouver mining division.
22. West Coast of Vancouver Island, Vancouver mining division.

The following localities in Yukon are also mentioned by O'Neill and Gunning (1934, p. 108–111):

1. Teslin (Hootalinqua) River and tributaries.
2. Kaskawulsh River and tributaries.
3. Kluane River and tributaries, Kluane mining division.

Alluvial platinum is also recorded from the bars of the North Saskatchewan River, Alberta.

YUKON

The principal nickel-copper deposit of Yukon (Yukon Territory) is the Wellgreen lode, which was discovered in 1952 and which is owned by the Hudson-Yukon Mining and Smelting Co. This property is in the Kluane Lake district, about 150 miles west of Whitehorse, Yukon Territory. Reserves of ore are reported to range from 500,000 to 737,000 tons, with tenors in nickel of 2.04 to 2.14 percent and of copper from 0.74 to 1.42 percent. Platinum and palladium are reported to range respectively from 0.038 to 0.049 ounce and 0.27 to 0.32 ounce per ton of ore. A pilot shipment of 300 tons, on which these tenors are presumably based, was tested at Flin Flon in 1955.

Another property in Yukon is that of the Canalask Nickel Mines, Ltd., in the Kluane Lake district. The ore reserves amount to 550,000 tons, with an average tenor of 1.68 percent nickel and 0.04 percent copper. The content of platinum metals has not been published.

OTHER PROVINCES

Other occurrences of the platinum metals are recorded by O'Neill and Gunning (1934, p. 54, 55, 75, 135) in the provinces of Nova Scotia, Saskatchewan, and Newfoundland. Two properites are mentioned in the eastern part of Halifax County, Nova Scotia, where small amounts of platinum occur in a scheelite-quartz vein.

Platinum metals were found in two drill holes near the Rottenstone Lake, about 80 miles north of Lac la Ronge, northern Saskatchewan. The country rock at these sites is gneiss and schist, and the nickel-copper ores that contain platinum and palladium appear to occur in oxidized zones within these rocks.

Small amounts of platinum are reported by Howley (1907, p. 783) to have been found in chromite in a serpentinized area in the vicinity of Mount Cormack, central Newfoundland.

REPUBLIC OF SOUTH AFRICA

The platinum metals are widely distributed in the Republic of South Africa, where they occur in the provinces of the Transvaal and Cape of Good Hope, in association with nickel-copper ores. In the same environment they extend northward into Rhodesia, and they are also recovered as a byproduct of the copper deposits in Katanga, Republic of the Congo, and in Zambia (formerly Northern Rhodesia). The platinum-bearing lodes occur in various environments, and the platinum metals, though mainly in the form of platinum mineral compounds, occur at some places as native platinum alloys. The most important of the platinum lodes are related genetically to the noritic and pyroxenitic formations of the Bushveld igneous complex (or series), of central Transvaal; and the principal productive areas are in the Rustenburg and Pilandsberg districts, at the southwestern and western sides of this complex.

The gold fields of the Witwatersrand are in south-central Transvaal, contiguous to Johannesburg, and they extend southward into the Orange Free State. These are ancient lithified placers mined as lodes, from some of which are produced significant amounts of native platinum metals as a byproduct of gold mining. This output, though relatively small, represents the world's largest production of osmiridium.

The first definitely recorded discovery of platinum in the central Transvaal was made in 1923 by Adolph Erasmus, a prospector, who panned it from a termite mound at a site about 8 miles west-northwest of Naboomspruit. The first discovery of platinum within the norite belt was made less than a year later by A. F. Lombaard, who panned it from the gravels of a dry watercourse in the western part of the Lydenburg district. The lodes of the Waterberg, Potgietersrust, and Rustenburg districts were discovered, respectively, in 1924, 1925, and 1926.

The mining of platinum was begun first in the alluvial and eluvial deposits, of which the most promising were in the Lydenburg district, though such deposits were also found at other localities. This mining proved to be unprofitable, because most of the platinum occurred in bedrock as very fine particles locked in sulfides, so that even if freed by weathering they were subject to downstream movement and dispersal. Mining of the lodes soon began in the Lydenburg, Pretoria, Rustenburg, Pilandsberg, Waterberg, and Potgietersrust districts. Wagner (1929) lists at various places in his book a dozen or more companies who undertook such mining, but practically all this work, except in the Rustenburg and Pilandsberg districts, was finally discontinued, either because it was unprofitable or because it was so much less profitable than the present mining at the west side of the Bushveld complex. The more promising of these deposits were eventually acquired by the Rustenburg Platinum Mines, Ltd., which now controls all lode mining in the Rustenburg and Pilandsberg districts. This company, in turn, is a subsidiary of a holding company known as the Johannesburg Consolidated Investment Corp., Ltd.

Practically all the platinum metals now being recovered from the lodes of the Transvaal come from a specific zone within the norite belt, called the Merensky zone, described on pages 39–42. This is a very regular igneous sheet that has been traced for 250 miles in the Rustenburg, Pilandsberg, Lydenburg, and Potgietersrust districts. The platinum ores of the Merensky zone and other lodes of the Transvaal represent the greatest known reserves of platinum metals in the world.

The production of platinum metals in the Republic of South Africa (other than osmiridium) has come largely from the nickel-copper lodes of the Transvaal, though a small but indeterminate part has come from placers and other sources. According to the data published by Quiring (1962, p. 96) and from other sources, the total production of the Republic of South Africa from 1925 to 1962, inclusive, has been 4,966,000 ounces, with a maximum output in 1957 of 603,700 ounces.

The production of platinum metals from the Transvaal has been limited in recent years by the demands of the world's metal markets. Since 1964, however, a program of expanded production has been in progress by the Rustenburg Platinum Mines, Ltd., and this has been corroborated by statements made by this company in the Platinum Metals Review, (v. 10, no. 2, p. 52–53, 1966, v. 11, no. 1, p. 9, p. 131, 1967; and v. 12; no. 4, p. 139). Permanent mining facilities are now being installed that will lead to a production of 1 million ounces by 1969. The ore reserves at Rustenburg alone are considered sufficient to maintain this output well beyond the year 2,000.

TRANSVAAL AND ORANGE FREE STATE PROVINCES

GENERAL GEOLOGY

The general geology of the Bushveld igneous complex and of the surrounding rocks is similar in some respects to that of the Sudbury district, but markedly different in others. Both these areas are characterized by a synclinal basin floored by basic igneous rocks, and both areas are surrounded by Precambrian rocks; but most of the other characteristic features are dissimilar, though a tendency has existed to correlate

the geologic and petrographic features of the Bushveld and Sudbury areas.

The general stratigraphy adopted in this paper is that proposed by Hall (1932), who worked for more than 30 years in the Transvaal, though it is evident from a late geologic map of the Transvaal, compiled in 1955 by E. C. Truter and P. J. Rossouw, that new interpretations have been made. A recent memoir of the Geological Survey of South Africa, by Coetzee (1960, 198 p.), gives the systems, series, and smaller stratigraphic divisions now accepted by the Geological Survey of South Africa, with special reference to the Orange Free State.

The oldest rocks of this region are the metamorphic rocks of the Swaziland system or Basal Complex. Unconformably above these are the sedimentary rocks of the Witwatersrand system; unconformably above these lie andesitic lavas, porphyries, and pyroclastics, together with the sedimentary rocks of the Ventersdorp system, and unconformably above these are the sedimentary and andesitic rocks of the Transvaal system, of which the Pretoria series is the uppermost division. The Basal Complex and the Witwatersrand, Ventersdorp, and Transvaal systems are of Precambrian age. The Transvaal system comprises rocks with a maximum thickness of 25,000 feet. The Pretoria series, which constitutes the upper part of the Transvaal system, consists of sedimentary rocks, lava flows, and sills with a total thickness of about 13,000 feet; and within the Pretoria series lie the basic and ultrabasic intrusives and extrusives that compose the Bushveld igneous complex.

The principal rocks of the Pretoria series are quartzite, shale, and conglomerate, of which the uppermost formation below the norite lopolith is the Magaliesberg quartzite, which at many places constitutes the floor of the norite. One feature of the Pretoria series, according to Hall's classification, is the presence of three formations of basic amygdaloidal lavas, separated from one another by sedimentary rocks. Between the two younger of these lava sheets occur sills of the same petrographic character as those which intrude the Magaliesberg quartzite and underlying shales. These lavas and sills, together with the sedimentary rocks that separate them, are commonly included as a part of the Bushveld igneous complex, as they are regarded by some geologists as the earliest manifestations of the igneous activity that later produced the main noritic and associated rocks of the Bushveld complex.

BUSHVELD COMPLEX

The basal horizons of the Bushveld igneous complex have already been defined. Above the Magaliesberg quartzite, and commonly in contact with it, occurs a great intrusive mass of norite and associated ultrabasic rocks, which constitutes the part of the Bushveld igneous complex that is the principal source of the platinum-bearing nickel-copper ores. Where the noritic and associated rocks are not in contact with the Magaliesberg quartzite, they are floored by the Dullstrom volcanic formation, which overlies the quartzite at some localities, and is the youngest of the three volcanic formations cited above.

The Bushveld complex also includes three younger formations. Above the noritic rocks, but at some places intruding them, is a formation generally called the Red Granite. This does not usually rest directly upon the noritic rock, as it is more commonly separated by a band of felsite, granophyre, or quartzite. It has the general configuration of a sill, however, with a thickness measurable in hundreds, rather than thousands of yards, and is generally regarded as younger than the noritic rocks. Above the Red Granite is a sheet of granophyre, with a thickness of about 1,200 feet, which is probably younger than the Red Granite. The uppermost igneous formation of the Bushveld complex is a mass of felsite and derived pyroclastics, which are older than the norite lopolith. These felsites and related rocks, with a thickness of about 8,500 feet, are interpreted as the surficial equivalents of the underlying granophyre. They also are regarded as the basal part of the Rooiberg group, which commonly forms the roof of the Bushveld igneous complex, and is considered to represent the uppermost part of the Pretoria series. The ages of the intrusive and extrusive rocks of the Bushveld complex, including the sedimentary rocks of the Rooiberg group, are considered by South African geologists to be of late Precambrian age.

The Rooiberg group is overlain successively by the Waterberg and Karroo systems, though the geologic map by F. C. Truter and P. J. Rossouw (South Africa Geological Survey 1955), shows that these two systems have been replaced by five other systems which, named in order of decreasing age, are the Loskop, Waterberg, Nama, Kaap, and Karroo systems. The Loskop and Waterberg systems are now considered to be of Precambrian age; the Nama and Kaap are called Devonian to middle Carboniferous; and the Karroo system is regarded as Triassic to early Jurassic. None of these systems figures prominently in the geology of the Bushveld igneous complex, except that they overlap and therefore conceal parts of the norite lopolith and its included Merensky zone. Still later geologic maps by the Geological Survey of South Africa (1960 and

1967) show further modifications of the stratigraphic sequence.

The formation of noritic and associated rocks lies in an ovaloid synclinal basin which trends east-northeast, with major and minor axes respectively of about 280 and 110 miles. The surficial extent of these rocks, as shown in figure 3 including the eastern and northeastern area with the western and northwestern area, is about 20,000 square miles. This intrusive is regularly layered and dips inward toward its center at angles ranging from 5° to 50°. The maximum thickness of these basic and ultrabasic rocks varies from one locality to another, ranging from 5,000 to 18,200 feet, with a mean thickness taken from the data presented by Hall (1932, p. 268) of about 11,800 feet. This intrusive therefore has the general form of a gigantic sill.

A thick central part of the noritic intrusive is generally believed to plunge to a great but undetermined depth and under this interpretation warrants the designation of a lopolith. There is, however, a zone north-northwest of Potgietersrust where only the upper part of the intrusive is present, as the lower zones were not developed in the form of a sill penetrating the country rock. Instead, this protuberance, which extends about 65 miles north-northwesterward from the projected rim of the lopolith, may best be regarded as a great dike that penetrated deeply into the country rock. West of Pilandsberg, only the lower part of the lopolith is present, and this is believed to have resulted from the erosion of the upper horizons. This lower zone includes inliers of quartzite and metamorphosed shale that indicate the irregular nature of the basal contact. The northern contact of the noritic formation with the rocks that underlie it is not exposed for about 130 miles, as it is overlapped in this stretch by younger sedimentary rocks. Owing to the same cause, a similar hiatus of about 90 miles exists along the southern contact. For these reasons, the minor axis of the lopolith, as given above, is materially different from that stated by Wagner and Hall, which applies to the noritic lopolith as a whole, and includes the intrusive branch that extends north-northwest from Potgietersrust.

The norite and related rocks are divided by Wagner (1929, p. 44) into three principal zones, which named from bottom to top are the differentiated or critical zone, the main belt, and the upper zone. Wagner thus includes in his differentiated zone the chill zone, transition zone, and critical belt proposed by Hall (1926).

A generalized section of the norite lopolith south and southwest of Pilandsberg has been presented by Wagner (1929, p. 45) as follows:

329-505—69——4

Composite section across norite lopolith near Pilandsberg

		Approximate thickness (feet)
Upper zone	Norite, grading upward into gabbro and syenite.	
Main belt	Diallage norite with stratiform segregations of titaniferous magnetite and labradorite-anorthosite.	8,000
	Diallage norite.	
	do	1,000
Differentiated or critical zone.	Bronzitite with bands of anorthosite and pseudo-porphyritic diallage norite (contains Merensky zone).	
	Bronzitite with seams and lenses of chromitite.	1,700
	Bronzitite with isolated lenses of harzburgite, differentiated diallage norite, and chromitite.	
	Bronzitite with lenses of harzburgite and anorthositic norite containing bands of bytonite-anorthite and labradorite anorthosite (contains Vlakfontein nickel zone).	630–1,000
	Bronzitite with lenses of harzburgite.	3,000
	Pyroxenitic olivine-norite probably grading downward into the basal or chill zone of diabasic quartz-norite.	400
Minimum thickness in this area		15,100

ORE DEPOSITS

Ore deposits that contain the platinum metals include numerous types with local variations, and the scattered over a great area along the periphery of the intrusive complex. The best understanding of these ores can be obtained by describing the petrography and mineralogy of type deposits, with emphasis upon the mode of occurrence of the platinum metals. This approach is much facilitated by a generalized genetic classification of the different ore deposits of the norite zone of the Bushveld complex. Emphasis is placed upon the productive ores of the Merensky zone, whereas the other types of deposits are only briefly described.

A general classification of the platinum deposits related to the basic and ultrabasic rocks is as follows:

Classification of platinum deposits of the noritic and related rocks

A. Magmatic segregates:
   1. Ores in which the platinum metals, mainly platinum and palladium, are associated with nickel-copper sulfides in norite and pyroxenite.
   2. Ores of chromitite, containing native platinum metals.
   3. Ores of dunite, containing native platinum metals.

B. Pneumatolytic, hydrothermal, and contact metamorphic deposits in sedimentary rocks subjacent to the basic and ultrabasic intrusives.

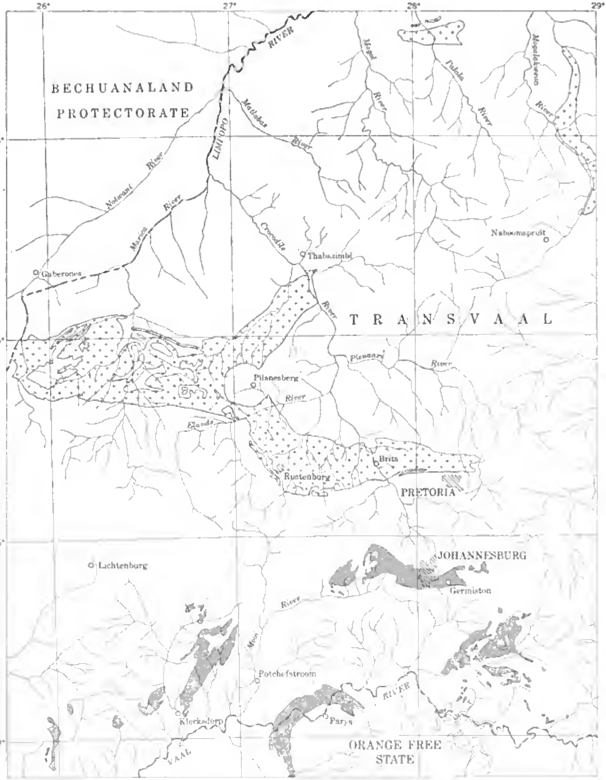

FIGURE 3.—Norite and differentiated ultrabasic rocks of the Bushveld igneous complex and the Witwatersrand System, Transvaal and Orange Free State, Republic of South Africa.

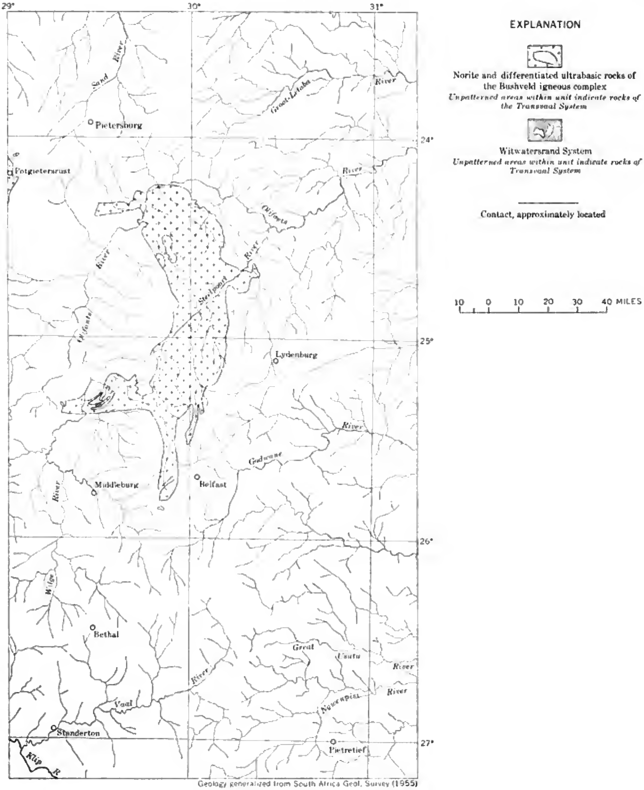

FIGURE 3.—Continued.

MAGMATIC SEGREGATES

The mineral deposits formed by magmatic segregation have been divided by Wagner (1929, p. 49) into the seven following types.

Classification of magmatically segregated platinum deposits

A. Upper noritic rocks:
   1. Deposits in quartz-bearing anorthositic norite.
   2. Deposits in a medium-grained feldspar-rich spotted norite.
   3. Deposits in a rather coarse-grained feldspar-rich diallage-norite.

B. Lower noritic rocks:
   4. Deposits of the Merensky type that occur above and below the main Merensky zone.
   5. The main Merensky zone, as developed in the Rustenburg, Pretoria, Lydenburg, Pietersburg, and Potgietersrust districts. The mineralized rocks are pseudoporphyritic pyroxenitic diallage-norite, feldspathic harzburgite and chromitite.
   6. Deposits in a fine-grained pyroxenitic diallage-norite, merging into coarse-grained feldspathic bronzitite and bronzitite.
   7. Deposits in bronzitite.

The first type of the magmatic differentiates is illustrated by a number of deposits about 35 miles north-northwest of Middleburg. The mineralized rock consists of irregular segregations of light-colored anorthositic quartz-bearing norite in a dark-colored diallage norite. The largest of these deposits has been proved by underground exploratory work to be of considerable size, but it has not been mined. Labradorite, the principal rock-forming mineral of the light-colored norite, is intergrown with diallage, a little quartz, and less chlorite. The ore minerals are chalcopyrite, pentlandite, and pyrrhotite, which appear as small specks scattered rather uniformly throughout the rock. Sperrylite, the only recognized platinum mineral, occurs in minute, brilliant, cubo-octahedra. The tenor in platinum is given as a maximum of 0.65 troy ounce per ton of ore.

The second type of magmatic differentiate is illustrated by the ores near the eastern limit of the noritic intrusive, southeast of the Steelport River. These deposits comprise at least five zones in the upper part of the norite which consists of irregular masses of medium-grained spotted feldspar-rich sulfidic norites that either underlie or are enclosed in lenses of spotted anorthosite. The mineralized rock is dominantly a granular aggregate of labradorite, intergrown with some bronzite, and less hornblende and diallage. The sulfides occur interstitially as irregular intergrowths of pyrrhotite, nickeliferous pyrite, pentlandite, and chalcopyrite. These mineralized zones are rarely longer than 8 feet nor thicker than 18 inches, and conform structurally with the general attitude of the country rock, which dips 15° west-northwest. The tenor in platinum ranges from 0.02 to 0.12 ounce per ton, and the deposits lack economic value.

The third type of ore deposit occurs in the same general vicinity as the one just described. The ores consist of small irregular bodies of coarse-grained feldspar-rich sulfidic diallage norite, enclosed in medium-grained spotted norite. The sulfide-bearing norite commonly encloses a thin seam of magnetite, and a great stratiform segregation of titaniferous magnetite lies a short distance higher in the sequence. The ore-carrier is a lustrous blue-green rock that consists of large tabular crystals of labradorite, anhedral grains of green diopside with rodlike inclusions, anhedral crystals of bronzite, and small grains of magnetite. Sulfides ranging in size up to 0.8 centimeter in maximum diameter are irregularly distributed in the rock. The character of the platinum minerals is not known, but they are believed to occur in the sulfides. A sample of the ore, taken over a thickness of 42 inches, had a tenor of 0.27 ounce of platinum per ton. This deposit is no longer worked.

The fourth type represents ores similar to those of the Merensky zone, which occur in the igneous sequence above and below the latter zone. They differ from the true Merensky zone in being lenticular and in having lower tenors in the platinum metals. Some of these ores were formerly mined.

A magmatic deposit of the sixth type occurs about 11 miles northwest of Potgietersrust, in association with the west-dipping dikelike extension of the noritic lopolith. This deposit is a thick sheet of fine-grained pyroxenitic diallage norite, merging locally into coarse-grained bronzitite and feldspathic bronzitite, and was traced for 1,700 feet. The norite intrudes beds of ironstone and quartzite and includes xenoliths of these rocks. The sulfide mineralization is sporadic, and platinum is erratically distributed in the ores. For these reasons, the deposit has no economic significance.

The seventh type of deposit, which occurs only in the Rustenburg district, consists of isolated pipe- and irregular-shaped masses composed partly of disseminated sulfides, partly of sulfides poikilitically intergrown with rock-forming minerals, and partly of massive sulfides. The enclosing country rock is bronzitite, with enclosed lenses of harzburgite and anorthositic norite. Small amounts of palladium and less

platinum are present in the sulfides, and also in sperrylite. These deposits are not rated as important sources of the platinum metals.

Merensky zone

The Merensky zone is an exceedingly persistent igneous sheet that lies near the top of Wagner's differentiated or critical zone. It therefore lies approximately 9,000 feet below the top of the lopolith in the Rustenburg district, and about 6,000 feet above its base. The Merensky zone has been traced intermittently for 140 miles in the Rustenburg and Pilandsberg districts, for 70 miles in the Lydenburg district, and for 40 miles in the Potgietersrust district. This zone has been prospected and proved to contain workable ore for 70 miles along its outcrop at the western end of the lopolith, where the Rustenburg and Union mines are located. Notwithstanding the general continuity of this sheet along its strike, marked differences exist in its thickness and petrographic cross section. A description of this zone throughout its entire length is far beyond the scope of this report, but such details, if needed, will be found in the volume by Wagner (1929).

Another well-known zone, at stratigraphic distances of 400 to 1,000 feet above the Merensky zone, consists of an anorthosite which is particularly resistant to weathering, forming large residual boulders at the surface. This is regarded as a valuable horizon marker in prospecting.

The Merensky reef, also called the Merensky platinum reef, where it exists as a distinct horizon, is a relatively thin sheet of coarsely crystalline pyroxenite with a pegmatitic habit that lies near the base of the Merensky zone. This reef, with a thickness of 1 to 2 feet, is the principal source of the platinum metals that are being recovered in present mining operations. The tenor in platinum metals, however, is somewhat higher in the upper than in the lower part of the reef. At the base of the reef is a seam of chromite, with a mean thickness of three-fourths of an inch, and at its top is a similar but thinner seam of chromite. These are called the lower and upper chrome bands and have high tenors in platinum, but are too thin to influence the average tenor greatly. Platinum metals extend upward from the Merensky reef for some inches into the overlying pyroxenite, and similarly downward into an underlying anorthosite.

The Merensky zone ranges in thickness from 2 to 35 feet. In general, this igneous sheet is a dark-colored norite, but the petrographic character varies both along the strike and across it. The relative amounts of pyroxene and feldspar are inconstant, and with an increase in feldspar the rock grades into anorthositic norite and anorthosite; with an increase in pyroxene it grades into pyroxenite. Locally the norite becomes peridotitic. The rock adjacent to the hanging wall is generally a light-colored spotted norite, composed of bronzite and diallage in a matrix of feldspar. Directly above the Merensky zone is a fine-grained pyroxenite, which by some writers is called the Merensky pyroxenite. This is overlain by anorthositic gabbro, which is overlain by a mottled or spotted anorthosite. These three sheets, with a combined thickness of 25 feet, are succeeded upward by another pyroxenite, with a thickness of 8 to 22 feet, which is called the Bastard reef. This well-known horizon resembles in several respects the Merensky zone, and even has a thin seam of chromite at its base. But it is either barren of platinum metals, or contains at most only very small amounts of them. Anorthosite commonly forms the base of the Merensky zone.

Two platinum lode mines, controlled by the Rustenburg Platinum Mines, Ltd., are now being operated in the Merensky zone of the Transvaal. The older of these mines, called the Rustenburg (formerly the Waterval) mine, is about 7 miles east of Rustenburg; the other, called the Union mine, is about 48 miles N. 5°W. of Rustenburg. The geological and other data on these deposits, as presented below, have been obtained from papers by the technical advisers to the Rustenburg Platinum Mines, Ltd. (1957), by Coertze (1958), by Cousins (1959 a, b, c), by Beath, Cousins, and Westwood (1961), and by Beath, Westwood, and Cousins (1961). Certain minor discrepancies in these papers have been resolved by the writer, according to his best judgement.

The ore body mined at the Rustenburg mine comprises the Merensky platinum reef with a thickness of about 12 inches, 8 to 9 inches of the overlying pyroxenite, and 8 to 9 inches of the underlying anorthosite making a total thickness of 28 to 30 inches. This platinum-bearing horizon is so regular that, over the last 10 years, the average stoping thickness of ore has been 28½ inches. The strike of the ore body is east-west, with a dip of 9°30′N., and mining has now reached a vertical depth of about 1,000 feet—a depth corresponding to about 6,000 feet down the dip. The extent of the mine along the strike is about 8 miles. Dikes and faults are rare, but at both mines there are roughly elliptical "potholes" of unknown origin that extend downward from the base of the Merensky reef, with diameters ranging from 20 to 100 feet and depths of 5 to 6 feet. Generally the ore at the bottoms of these potholes can be recovered. There are also subcircular dome-shaped masses, known as "koppies," which project upward from the anorthosite on

the footwall, and may be high enough to replace entirely the Merensky reef, and rarely to extend upward into the overlying pyroxenite. The rocks bounding the potholes and koppies are unfolded. Potholes and koppies are more prevalent at the Rustenburg than at the Union mine.

The ore body at the Union mine is markedly different from that at the Rustenburg mine. The pegmatitic pyroxenite which constitutes the Merensky zone has a thickness ranging from 10 feet in the southwestern part of the property to 20 feet in the northeastern part. The ore body here strikes northeast and dips about 21° SE. Up to 1965, the mine had been worked to a depth of about 700 feet —a depth corresponding to a distance of 2,000 feet down the slope of the intrusive and for a distance of 2½ miles along its strike. The platinum metals occur both at the top and at the bottom of this thick sheet but are concentrated near its upper contact, so that it is generally unprofitable to work the leaner ore at its base. Potholes in the Union mine are larger than in the Rustenburg mine, with diameters ranging from 200 to 700 feet and with correspondingly greater depths. Any ore that occurs at their bases cannot readily be recovered.

The platinum minerals at both mines are sperrylite, braggite, stibiopalladinite, and laurite, which occur as discrete grains and intergrowths in disseminated sulfides. The platinum metals probably occur also as molecular intergrowths replacing certain cations in the sulfides. Some native platinum metals are recovered, together with a little native gold. The platinum metals are mainly ferroplatinum, containing from 10 to 30 percent iron. Native ferroplatinum is more plentiful at the Union than at the Rustenburg mine, but the exact amounts or proportions have not been ascertained. The sulfides comprise chalcopyrite, pyrrhotite, pentlandite, nickeliferous pyrite, cubanite, graphite, millerite, and violarite. The tenor of the ore in platinum metals, in the stretch from Rustenburg to Brits, is reported to range from 0.25 to 0.35 ounce per ton. The tenors of similar lodes in the Lyndenburg and Potgietersrust districts are lower. These metals are strongly concentrated in the bounding chromite seams, particularly in the lower chrome band, where a tenor of 0.6 ounce per ton has been reported. The nickel and copper produced have a constant ratio to the amount of platinum metals recovered, but this ratio is higher at the Rustenburg than at the Union mine. In both mines, the ratio of nickel to copper is 1.8:1.

The oxidation of the platinum-bearing sulfides is a matter of interest. The footwall of the Merensky zone is composed at many places of bronzite and less diallage, sparingly but rather uniformly included in a matrix of labradorite-bytonite. Within the zone of oxidation, beneath the present level of ground water, this rock is mottled by streaks of limonite for a depth ranging downward as much as 2½ feet below the Merensky zone. This weathered zone contains specks of sulfides and small amounts of platinum metals. At the Rustenburg mine the zone of oxidation extends about 700 feet down the dip, a distance corresponding to a vertical depth of about 120 feet in general, in the Rustenburg district, this depth ranges from 70 to 140 feet. The fact that the top of the present water table, however, is from 40 to 60 feet below the surface shows that the visible oxidation of the ore was accomplished when the water table was lower than at present, presumably during an earlier and more arid climate. The composition of the platinum metals in the sulfide ore and in the weathered ore are notably different. Two analyses from the Rustenburg district, which are the means of four analyses published by Wagner (1929, p. 110), have been recomputed to 100 percent to show these differences (table 19). The platinum: palladium ratios in these two analyses are respectively 3:1 and 5.7:1. It is clear that a part of the palladium, and possibly some of the rhodium, was dissolved by mineralized ground water. This process relatively enriched the more resistant platinum.

TABLE 19.—*Composition, in percent, of platinum metals in sulfide and oxidized ores, Rustenburg district*

[N.D., no data]

	Sulfide ore	Oxidized ore
Platinum	69.74	79.92
Iridium	N.D.	1.29
Iridium and osmium	3.08	2.84
Rhodium	4.10	1.92
Palladium	23.08	14.03
Total	100.00	100.00

The preceding statements, which accept the origin of the platiniferous horizons in the Bushveld complex as differentiated igneous sheets, are now being reexamined more closely by workers at the Union and Rustenburg mines, and in nearby areas where data based upon drilling on a large scale is being done. Coertze (1958, p. 387–400) has proposed that each of the basic types of the Bushveld igneous complex, including pyroxenite with chromite seams, anorthosite, norite, porphyritic, pyroxenite, pegmatitic pyroxenite, gabbro, ferrogabbro, dunite, and magnetite, represents a separate intrusion. More recently it has been stated by Beath, Cousins, and Westwood (1961, p. 2) that recent geophysical and collateral evidence tend to contradict

the lopolithic concept of the noritic rocks of the Bushveld igneous complex. Instead it is inferred that the eastern and western limbs of this intrusive represent separate T-shaped curved dikes that extend to great depths, and that basic and ultrabasic rocks do not underlie the central part of the basin. The cited authors appear to agree with the interpretation of Coertze, but also suggest as an alternative hypothesis that these rocks may be of extrusive origin, which would account for the phenomenal regularity of the successive sheets and for the absence of crosscutting by dikes. It is admitted, however, that the true genesis of the Bushveld igneous complex remains still within the realm of speculation.

Chemical analyses

The mean ratios of the platinum metals from the lodes of the Transvaal are much better known than the ratios from the Sudbury district. The sales of platinum metals, both from the lodes and from the Witwatersrand lithifield placers, have been published regularly by the Department of Mines and Industries, of the Republic of South Africa, and have been quoted annually by the U.S. Bureau of Mines in the sequence of Minerals Yearbooks. The following data on the lodes comprise those of 20 years in the interval 1929–56, and therefore may include for a few years some of the platinum metals from mining operations now discontinued, but in general these data represent the production from the Rustenburg and Pilandsberg districts. These records, recomputed to simulate analyses, are shown in table 20.

The ratio of platinum to palladium in the Merensky zone is reported by Wagner (1929, p. 129) to range from 6.5:1 to 1.6:1 and is shown in the Potgietersrust district to be as low as 1.3:1. Table 20 shows a ratio for the Rustenburg district of 3.6:1, which is substantially different from that at Sudbury, where it is about 1.1:1. The data on the relative prevalence of rhodium and ruthenium are not as dependable as could be desired, but according to table 20, the amount of rhodium exceeds that of ruthenium, though rhodium is much less plentiful than at Sudbury. The proportions of the metals recovered from the placers of Goodnews Bay, Alaska, and from the Uralian placers, as shown respectively on pages 59 and 88, are markedly different from those recovered from the lodes of the Transvaal and Sudbury. This fact constitutes a significant difference that distinguishes the native platinum metals of the peridotites and perknites from the platinum metals recovered from the platinum minerals of lodes.

TABLE 20.—*Composition, in percent, of platinum metals, mainly from Rustenburg district*

[N.D., no data]

	1929	1930	1931	1934	1935	1936	1937	1938	1939	1940
Platinum	82.92	80.96	74.99	86.82	79.83	77.75	77.08	72.53	78.20	66.27
Iridium	.56	.24	.21	.01	.08	.05	.06	.20	.13	.42
Osmium and iridium	.46	.45	.08	.01	.02	....	.14	.12	.08	.22
Ruthenium	.59	.47	1.39	.41	.08	.91	.51	1.72	1.20	2.20
Rhodium	1.10	.64	.15	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	.64
Palladium	12.77	12.51	15.96	12.00	13.59	15.82	16.70	19.78	16.33	25.71
Total	98.40	95.27	92.78	99.25	93.60	94.53	94.49	94.35	95.94	95.46

	1944	1945	1947	1948	1949	1951	1952	1954	1955	1956	Adjusted mean
Platinum	63.58	59.72	77.08	69.17	61.27	68.89	66.27	78.18	60.98	69.50	75.06
Iridium	.38	.74	.06	.47	.30	.31	.13	N.D.	N.D.	N.D.	.27
Osmium and iridium	.03	.12	.14	.09	.10	.11	.11	.03	.08	N.D.	.13
Ruthenium	4.39	4.10	.51	1.29	1.80	1.51	1.34	1.62	.59	.50	1.41
Rhodium	1.12	1.79	N.D.	2.57	3.32	1.79	2.39	2.66	2.38	2.30	2.15
Palladium	27.01	28.59	16.70	22.03	29.21	23.14	26.40	13.81	33.35	24.30	20.98
Total	96.51	95.06	94.49	95.62	96.00	95.75	96.64	96.30	97.38	96.60	100.00

CHROMITITE ORES

The more important platinum-bearing chromitite ores of the Bushveld complex are in the Lydenburg district, though similar bands have also been recognized in the Rustenburg district. Two principal zones of platiniferous chromitite, called the upper and lower chromitite horizons which lie in the lower fourth of the norite lopolith, are present in both districts. A third band, lying between the upper and lower horizons, has also been found in the Rustenburg district. These and other deposits of chromite are widely and persistently distributed along the strike of the intrusives in both districts, ranging in length from 3 feet

to several miles and in thickness from 1 inch to 14 feet. The fact that a typical deposit in the upper horizon, about 50 miles N. 28° W. of Lydenburg, occurs about a mile east of the outcrop of the Merensky zone and about 1,200 feet stratigraphically below the latter indicates an areal dip of 13° westward. In this deposit are two lenses of chromitite, with thicknesses of 2 and 3 feet, separated by 17 feet of bronzitite and norite.

The platinum-bearing chromitite consists generally of oval-shaped grains of bronzite crowded with minute poikilitic inclusions of chromite in a scanty matrix of larger included grains. Locally the rock is interspersed with irregular patches and streaks of coarse-grained chromite and picotite. The rock also contains minor amounts of diallage and calcic plagioclase. The content of Cr_2O_3 ranges in these deposits from 38 to 47 percent.

Native platinum metals characterize the chromitite deposits. These commonly occur in very thin plates and in slender wires of which some have only the thickness of a hair. Analyses have shown that platinum predominates over palladium, but at one deposit in the Lydenburg district, palladium constituted 55 percent of the platinum metals. No analyses are available that give the tenors of iridium, osmium, ruthenium, and rhodium. Tenors of platinum metals in chromitite are stated by Wagner (1929, p. 93-95) to range from 0.06 to 5.75 ounces per ton, but no average tenor may be cited. These deposits were intensively prospected in 1925 and 1926, but since the discovery of the Merensky reef in the Rustenburg district, no further attention has been given to them.

DUNITE ORES

Platiniferous dunites and related rocks have been found at many sites in the Lydenburg and Rustenburg districts. These deposits have a stratiform range of 2,000 feet in the lower part of the noritic lopolith, mainly below the Merensky zone, but a few occur above that horizon in the Lydenburg district. The most important deposits, however, lie between the upper and lower chromitite horizons.

These deposits are divided by Wagner (1929, p.51–52) into three types which depend primarily upon the nature of the olivine in the dunite. These varieties of olivine are, first, the normal type, wherein the ratio of MgO to FeO ranges from 12:1 to 2.5:1; second, hyalosiderite, with a MgO-FeO ratio ranging from 2.5:1 to 1.1; and third, hortonolite, in which the MgO-FeO ratio ranges from 1:1 to 1:2. The first type is characteristic of the dunites of the Ural Mountains and occurs only sporadically in the Transvaal; the second type is exemplified by only one important deposit, known as the Driekop deposit, which is about 32 miles N. 28° W. of Lydenburg; but more than 60 occurrences of ores of hortonolite dunite are known, both in the Lydenburg and Rustenburg districts. The two most important deposits of platiniferous hortonolite dunite, called the Mooihoek and Onverwacht lodes, occur about 3 and 6 miles respectively south of the Driekop deposit.

The Driekop deposit is essentially an intrusive core of platinum-bearing hyalosideritic dunite, enclosed in a much larger pipe of nearly barren dunite. The workable surficial area measures approximately 80 by 60 feet, but narrows somewhat with depth. The dip of the dunite core and probably also of the dunite pipe is about 77° NE. The platinum-bearing core has been followed downward to a depth of 460 feet without any great constriction. The ore body consists dominantly of interlocking grains of hyalosiderite with a MgO:FeO ratio of 2.4:1, together with small amounts of large greenish-gray crystals of diallage and also small anhedral grains of magnetite. Locally the diallage is sufficiently plentiful that the rock becomes a wehrlite.

A recent study of the Driekop deposit has been made by Heckroodt (1959, p. 59–71), and it is also from the dunite at this site that Stumpfl (1961, p. 833–847) identified the nine new platinum minerals that he described. In an area of 20 square miles surrounding this deposit, Heckroodt was able to recognize five successive phases in the basic and ultrabasic rocks, which were identified in the order of their intrusion as pyroxenite, norite and related rocks, pegmatitic feldspathic pyroxenite (Merensky zone), peridotite including dunite and serpentinite, and gabbroic rocks.

The platinum metals occur mainly as native alloys, within small segregations, lenses, and irregular clumps of iron-rich dunite and wehrlite of markedly coarser grain, such that the olivine is particularly conspicuous by reflected light. Below water level, small amounts of sperrylite and cooperite are also present. Nine assays of average ore show a range in platinum metals from 0.02 to 0.53 ounces per ton, with a mean tenor of 0.17 ounce per ton. Picked samples, however, range upward to 2.7 ounces per ton. The ratios of platinum to palladium and other platinum metals have not been published.

The Mooihoek ore deposit is a pipe of platiniferous hortonolite dunite, which is nearly circular in horizontal section, with a diameter of about 42 by 51 feet. This is enclosed in a layered cylindrical pipe of dunite and serpentinite, whose surficial horizontal measurements are 700 feet from north to south and 600 to

850 feet from east to west. The larger pipe is bounded by coarse pegmatitic diallage and feldspathic pyroxenite, which merge outward into olivine gabbro and spotted norite. The dimensions cited for the smaller pipe are those which delimit the workable ore, rather than dimensions based upon petrographic homogeneity, as the bounding dunite also contains small amounts of the platinum metals. The small platiniferous pipe of workable ore plunges N. 76° E. at an angle of 80°, and therefore lies nearly normal to the pseudostratification of the gabbroic country rock. This pipe is composed mainly of coarse-grained brown hortonolite dunite, which is interspersed with large clusters of black anhedral hornblende, books and aggregates of phlogopite ranging up to 6 inches in diameter, and clots and larger masses of lustrous titaniferous magnetite. Segregates of ilmenitite up to 3 feet in diameter are present. The hortonolite dunite merges rather gradually outward into the bounding olivine dunite. Pegmatitic veins composed of large crystals of diallage, phlogopite, hornblende, magnetite, and ilmenite in two systems of veins, with thicknesses from 1 inch to 4 feet, run parallel to the ore body. These veins appear to contain little platinum.

Most of the platinum metals occur in the native state, but Wagner (1929, p. 219) records the fact that platiniferous sulfides occur in veins and chromitic schlieren along the hanging wall of the large pipe. Sperrylite and cooperite have also been identified in the main ore body below water level. The sulfides include pyrrhotite, pentlandite, and a little chalcopyrite. The tenor of platinum in the workable pipe of the Mooihoek mine ranged from 0.01 to 1.0 ounce per ton of ore, with an average tenor of about 0.13 ounce. The platinum metals occur throughout the workable pipe, but they increase from the margin of the pipe inwards to the center, where they are highest. Thus, a winze sunk down the middle of the pipe showed an average value of 2.1 ounces per ton, whereas the mean tenor for the 350-foot level of the mine was 0.34 ounce. The character and percentages of the six platinum metals have not been recorded. A section of the mine, published by Wagner (1929, p. 72), shows the underground workings down to the 450-foot level and crosscut. Mining has been discontinued.

The Onverwacht mine was located on another pipe, similar to that at the Mooihoek mine. This pipe is an irregular but roughly parsnip-shaped segregate, or possibly intrusive, of hortonolite dunite and hortonolite wehrlite, within a much larger, steeply inclined pipe of olivine dunite that bears a transgressive or discordant relationship to the surrounding country rock. The olivine dunite at and near the surface is altered to serpentinite, which is cut by a network of veins and seams of magnesite. These secondary features disappear in the mine below a depth of 300 feet. The hortonolitic ore body crops out as a roughly circular area of coarse-grained rock with a radius of about 25 feet, surrounded by a finer grained shell of the same rock with a thickness of about 5 feet. This pipe plunges S. 28° E. at an angle of about 78° which is roughly normal to the stratiform sheets of bronzitite that constitute the country rock. Wagner (1929, p. 64) believes that these stratiform sheets were intruded in a horizontal position, and therefore that the pipes of olivine dunite, hortonolite dunite, and wehrlite had originally a vertical attitude. The radius of the hortonolitic pipe increased downward for a short distance, and then decreased to the 350-foot level of the mine, where it split into three smaller bodies. The largest of these roots continued downward to and below the 750-foot level, where it had a radius of about 11.5 feet. The other two roots disappeared below the 450-foot level.

The principal or central part of the ore body consists of rather coarse-grained hortonolite dunite and wehrlite, wherein the hortonolite occurs as crystals that range in size up to a maximum diameter of 2 inches. Black anhedral crystals of hornblende are also present, and the rock is interspersed with patches and schlieren of phlogopite in leaves up to 8 inches in diameter. On the 200-foot level the ore contained clots of titaniferous magnetite, and on the 250-foot level and elsewhere in the mine, the ore included large xenoliths and slabs of chromitite.

The platinum metals are so distributed that the tenors are highest in the central or axial zone of the pipe and decrease toward its periphery. In the upper levels the central part of the pipe had an average tenor of 1 ounce of platinum metals per ton of ore. Another zone of enrichment was in and along the borders of the bodies of chromitite; and along one such contact, ore was found that had a tenor of 55 ounces per ton. The best average ore was on the 250-foot level, where the mean tenor was 0.92 ounce per ton. With depth, however, the ore grew leaner; and between the 550-foot and 700-foot levels, the lode was barren, though workable ore was again found between the 700-foot and 800-foot levels. Mining has been discontinued.

Native platinum alloys constitute most of the platinum metals recovered from the upper levels of the Onverwacht mine, but in the lower levels about 25 percent of these metals come from sperrylite and cooperite. The number and character of the platinum alloys have not been determined, but two inferior analyses of some of the native metals have been pub-

lished by Wagner (1929, p. 19). These samples were handpicked, and therefore the base metals may be regarded mainly as dross. The mean of these two analyses, with and without the dross, are shown respectively as A and B in table 21.

TABLE 21.—*Analyses, in percent, of platinum metals at Onverwacht mine*

	A	B
Platinum	84.46	97.40
Iridium plus osmium	1.63	1.88
Rhodium	.20	.23
Palladium	.42	.49
Iron	12.41	--------
Copper	.64	--------
Nickel	.24	--------
Total	100.00	100.00

PNEUMATOLYTIC, HYDROTHERMAL, AND CONTACT METAMORPHIC ORES

Pneumatolytic and hydrothermal ores are best exemplified by a group of deposits in the Waterberg district, about 8 miles west-northwest of Naboomspruit. These consist of brecciated quartz lodes that lie in felsite and felsitic tuff, close to the Red granite, in the upper part of the Bushveld igneous complex. The principal one of these lodes and another lode branching from it were worked in 1924–26, but mining was finally discontinued because the platinum ores, though of high tenor, were erratically distributed with much ore of very low grade between the rich ore shoots.

The principal lode has a thickness of 6 to 60 feet, and can be traced at the surface in a direction about N. 55° E. for 2½ miles. The dip of the ore body is from 60° to 75° SE. A branch from the main lode has a thickness of 4 to 30 feet, and is traceable east-northeast for a distance of about 1,240 feet. Some of the richest ore came from this branch lode. Both the main lode and its branch consist of closely spaced stringers of quartz, separated by irregular bodies of felsite. The ore consists of opaque white quartz in a comb structure with the crystals oriented normal to the walls. Other phases of the ore led to the conclusion that there were at least four stages of brecciation and deposition of quartz and chalcedony. The ore minerals are specularite and other iron oxides, sericite, chromiferous chlorite, kaolin, and pyrolusite.

Native platinum alloys occur in these ores in grains ranging in size from 0.04 to 0.6 millimeter. A part of the platinum metals are intergrown with specularite; another part of later origin is embedded in iron oxide derived from the oxidation of pyrite. Chemical analyses indicate that the ratios of platinum to palladium in the main and branch lodes are respectively 13:1 and 1.6:1. The other platinum metals were apparently not identified, but may be present in small amounts. The tenors in gold range from 0.4 percent in the main lode to 3.0 percent in the branch lode, so that these are platinum ores with gold as merely a small byproduct. The tenor of the platinum metals in high-grade ore shoots was remarkably high. Ore taken over a stretch of 50 feet in the main lode, over a width of 20 inches, had a tenor in platinum metals of 5.4 ounces per ton, and for the same distance along the branch lode, over a width of 35 inches, the ore had a tenor in platinum metals of 51 ounces per ton. Picked samples had still higher values.

The genesis of these siliceous platinum ores is problematical. The brecciation and the ore minerals led to a belief that they were formed at no great distance below the surface initially as pneumatolytic deposits and were followed in the waning stages of mineralization by hydrothermal deposition. Hot springs are still present in the vicinity of these lodes. The general character of the ores suggests their derivation from an underlying persilicic intrusive, but the presence of chromitiferous chlorite suggests that the ores may have come from basic or ultrabasic intrusives. A composite origin is strongly suggested. Siliceous lodes that contain platinum are known elsewhere in the world, and in fact, 23 such occurrences are tabulated on page 98 of this report. Most of these deposits, however, are gold-quartz veins, with a byproduct of platinum metals.

A contact metasomatic deposit occurs near the magmatic deposit 11 miles northwest of Potgietersrust, that was described above. This ore body is in the so-called Dolomite series, which is that part of the Transvaal system which directly underlies the Pretoria series. The ore deposit consists of several zones of crushed dolomite in a thick bed of banded ironstone, which dips steeply west, and the ore comprises lenses, eyes, and irregular bodies of graphic granite and pegmatite that contain copper and nickel sulfides, with which are associated sperrylite and stibiopalladinite. This locality is the site of the original discovery of stibiopalladinite. The deposit is considered to be too low grade for mining.

The Merensky reef has been traced intermittently for 25 miles north-northwest of Potgietersrust, and also for a short stretch south of that town. A platinum deposit that is genetically related to the Merensky reef, but not an integral part of the reef, is particularly well developed in the zone between Vaalkop and Zwartfontein, where it was formerly mined. This deposit is a sinuous lens about 11,000 feet long and about 145 feet thick, which conforms with the pseudostratification of the intrusive sheets, and strikes generally

north-northwest with a westward dip of about 55°. The ore body may be either of magmatic or contact metamorphic origin. In its southern part, where dominantly pseudomagmatic, the ore carrier is coarse-grained feldspathic pyroxenite and pegmatitic norite, with a hanging wall of coarse-grained anorthositic norite and a footwall of fine-grained rock of the same kind, but in its northern zone, the ore is composite, consisting in part of platinum-bearing bronzitite and in part of overlying and underlying silicated dolomite that is also platinum bearing. The true Merensky reef in this area lies generally above the Vaalkop-Zwartfontein body, and commonly contains few or no platinum metals.

Platinum metals occur in the southern sector in concentrations of pyrrhotite, pentlandite, chalcopyrite, and cubanite, which commonly are intergrown with hornblende both in the principal ore carrier and in the contiguous hanging wall and footwall. The platinum minerals are reported to be sperrylite and cooperite, but they include both platinum and palladium which are probably included in a number of different minerals. In the northern sector, where the ore of highest grade occurs, the sulfides that are contained in the intrusive rocks and dolomite are not uniformly distributed, but occur instead in irregular ore shoots, the locations of which require careful prospecting and sampling. Northern, central, and southern parts of the northern, or Zwartfontein, sector are described in detail by Wagner (1929, p. 168–182), and cannot very well be summarized. The central and most important ore body of this northern sector has a known length of 3,500 feet, a thickness of 90 feet, and an average dip of 70° westward. For the whole ore deposit the platinum-bearing sulfides are as given above, and range in size from 1.0 millimeter to 1.5 centimeters, but in the contact metamorphic ores, the average size is about 4 millimeters. The mean tenor is platinum metals for the entire ore body is about 0.35 ounce per ton of ore, but in picked samples is as large as 2 ounces. From the concentrates produced in the last quarter of 1928, the ratios of the platinum metals, according to Wagner (1929, p. 111), are platinum 55.4 percent, iridium, osmium, ruthenium, and rhodium 2.4 percent, and palladium 42.2 per cent. This deposit was actively worked before the discovery of the Merensky zone in the Rustenberg district, but mining in later years has been discontinued.

PLACERS OF THE WITWATERSRAND DISTRICT

Detrital platinum has been found at numerous localities in South Africa, but none of these deposits is of present commercial value. Reference has already been made to the placers of the Lydenburg district, where platinum mining was first begun, though soon discontinued. A well-known lithified osmiridium placer is the so-called Black Reef conglomerate which is a part of the Black Reef series, that constitutes the upper 15 percent of the Transvaal system. This deposit is the site of a mine operated by the Government Gold Mining Areas (Modderfontein) Consolidated, Ltd., north of Johannesburg. The tenor of osmiridium at this property is high. The principal commercial lithified placers, however, are those of the Witwatersrand, which occur in the southern part of the Transvaal and the northern part of the Orange Free State.

HISTORY AND PRODUCTION

The gold deposits of the Witwatersrand consist of lithified placers that are mined as lode deposits. Osmiridium in this area, according to Wagner (1929, p. 33), was first identified by William Bettel in concentrates from the conglomerate (banket) of the New Rietfontein mine, in Orange Free State, in 1892. The first published description of the osmiridium was given by Young (1907, p. 17–30), but additional data were soon published by other workers. No attempt was made to save this osmiridium from 1892 to 1920, because the gold was saved by amalgamation, which was unsuited to the recovery of platinum metals. Beginning in 1921, however, a preliminary concentration began to be made on corduroy and blankets. This process permitted a production of osmiridium. The East Rand Proprietary Mines, one of the largest gold-mining companies in the world, controls 8,785 claims and has underground workings that extend 7½ miles along the strike of the auriferous reef and 3½ miles along its dip. These workings, as recently described by Anderson (1958, p. 321–325), underlie about 20 square miles of the municipalities of Germiston and Boksburg, southeast of Johannesburg. In May 1958, this mining had reached a depth of 11,000 feet, equivalent to about 1 miles below sea level. Much of the osmiridium produced in the Witwatersrand district comes from the different properties of the East Rand Proprietary Mines. The conglomerate of one of these, which is the site of the Modderfontein "B" mine, has been proved to have the highest tenor in osmiridium, as well as gold. Osmiridium is also recovered from properties in the West Rand.

The search for deeper deposits continues, and in 1962 the Anglo-American Corp. of South Africa, Ltd., sank a drill hole to a depth of 14,100 feet. The site of this hole was about 120 miles southwest of Johannesburg, and about 5 miles east of Bothaville, Orange Free State. This probe passed through the Karroo. Trans-

vaal, and Ventersdorp systems to reach the gold-bearing conglomerates of the Witwatersrand system.

The output of osmiridium from the Witwatersrand, in the Transvaal and Orange Free State, has remained sensibly constant since 1925, and is likely to continue so, because it is a byproduct of the regional production of gold, which changes little. In 1958 and 1959, however, the output of osmiridium decreased because the production of gold was curtailed, but both the osmiridium and the gold outputs are again increasing.

The production of osmiridium from the Witwatersrand from 1921 to 1960 has been shown by Quiring (1962, p. 101) to be approximately 231,125 ounces. Adding to this the outputs for 1961–65, the total production from 1921 to 1965 inclusive is seen to be 248,625 ounces. A maximum production of 7,780 ounces was made in 1942.

GENERAL GEOLOGY

The Witwatersrand system, consisting of bedded rocks of terrestrial origin, rests unconformably upon the rocks of the Swaziland system, which is the basal complex of this region. The Ventersdorp system, overlying the Witwatersrand system, consists dominantly of andesitic lavas and pyroclastics, and both systems are considered to be of late Precambrian age. According to Furon (1963, p. 341), the thickness of the Witwatersrand system is about 28,000 feet; and according to Coetzee (1960, p. 31–92), the thickness of these two systems is about 40,000 feet. Many local disconformities and unconformities exist in the Witwatersrand system, and the beds therefore show divergent thicknesses at different localities. The auriferous conglomerates of the Witwatersrand are ancient lithified placers, which comprise numerous strata with an aggregate thickness of about 2,000 feet and a maximum individual thickness of about 65 feet.

The rocks of the Witwatersrand system, in the Transvaal and Orange Free State, are folded into a large syncline with a major axis trending east-west, a length of about 110 miles and a width of about 45 miles. In the Johannesburg area, these rocks form the north flank of the syncline, and dip steeply south, though they flatten with depth to 30°. Near Parys, the synclinal structure is modified locally by a quaquaversal anticline. Owing to erosion and to the cited dome, the rocks of the Witwatersrand system crop out mainly at four separated areas, that is, near Johannesburg, Heidelburg, Parys, and in an area between Ventersdorp and Klerksdorp.

DEPOSITS

The gold and platinum of the Witwatersrand occur in thin beds of conglomerate and grit, known as reefs, which form the upper part of the Witwatersrand system. Several groups of these reefs have been recognized, including the Main Reef and Livingston group, near the base of the Upper Witwatersrand series, the Bird Reef group 1,600 feet higher in the sequence, and the Kimberly or Battery Reef group 5,000 feet stratigraphically above the Main Reef group. The principal production comes from the Main Reef group of reefs, which are mined in the Johannesburg area over an east-west extent of about 50 miles. The Main Reef group includes three productive reefs, which named from bottom to top are the Main Reef proper, the Main Reef Leader, and the South Reef. In the central part of the Johannesburg area, these three reefs are of equal size, but the Main and South Reefs extend eastward only as far as Boksburg, and the Main Reef extends westward about 11 miles. The Main Reef Leader has the greatest overall extent, and has been the principal producer of gold.

These reefs are locally persistent, but are nonpersistent over great distances, and vary considerably in thickness. Individual ore shoots have east-west and north-south dimensions that range respectively up to 5,000 and 1,000 feet. The beds of conglomerate in the Upper Witwatersrand system range in thickness from an inch to 15 feet, and in the Main Reef group from 1 to 10 feet, with thin intercalations of quartzite. The average thickness of the Main Reef, the Main Reef Leader, and the South Reef are respectively 4, 2, and 3 feet. The platinum metals are exceedingly scarce, but are most prevalent in the Main Reef Leader on the Far East Rand, less so on the West Rand, and are least plentiful in the Central Rand, where all the reefs of the Main Reef group are thickest.

Both the gold and the platinum metals are found to be most plentiful in conglomerates that have large pebbles. In the Main Reef Leader, these pebbles have a mean diameter of 2 inches, and consist mainly of quartz, with less quartzite, chert, and slate. The sandy matrix, in which the noble metals mainly occur, contains a large volume of secondary pyrite, estimated in the Main Reef Leader to constitute 3 percent of the ore. The gold occurs in minute angular crystalline aggregates, generally in direct association with the pyrite. Other ore minerals that are present in small amounts are pyrrhotite, galena, sphalerite, chalcopyrite, cobalt arsenide, uraninite, and the platinum metals. The sandy matrix has been recrystallized, with the development of secondary quartz, sericite, chlorite, chloritoid, carbon, and calcite. Tourmaline, zircon, and rutile are also present, but these are probably original accessory minerals of the conglomerates. Less resistant accessory minerals, such as the iron ores, have been de-

stroyed in the process of recrystallization, and probably constitute the sources of the pyrite. The gold is exceedingly fine grained, and has not in general retained its original detrital form. The platinum metals, however, have resisted recrystallization and show rounded outlines, or at least rounded edges of the crystalline grains, that indicate their detrital origin.

The platinum metals are exceedingly fine grained and range in size at one mine, according to Wagner (1929, p. 36), from 0.04 to 0.19 millimeter in diameter. At a mean diameter of 0.12 millimeter, such particles would have a value of about 0.012 cent, meaning that it would take 800,000 particles to weigh a troy ounce. The tenor of platinum metals is almost unbelievably low. Thus in the Modderfontein "B" banket, which contains more osmiridium than at any other mine in the Witwatersrand, the recovery, according to Wagner (1929, p. 35–36), is from 1 ounce per 1,212 tons of milled ore to 1 ounce per 9,285 tons of milled ore, or from 0.000003 to 0.0000004 percent. These figures, however, represent the amounts recovered, which probably are only about half of those actually present in the conglomerates.

The detrital origin of the gold and platinum metals of the Witwatersrand is favored by practically all South African geologists who have had a professional familiarity with these ores. The acknowledged fact of recrystallization, with solution and redeposition of the gold, however, has led some to believe that the noble metals are epigenetic and hydrothermal in origin, with sources extraneous to the conglomerate. Probably the most ambitious formulation of an epigenetic hypothesis was made by Graton (1930, 185 p.), who, notwithstanding his many contributions to the theory of ore deposits, was unfamiliar with placers. Consequently, he failed to evaluate the evidence for a detrital origin of these deposits; in particular, he overlooked the rounded and subrounded form of the grains of platinum metals. A few other geologists, in particular Davidson (1953 and 1955), have also accepted Graton's interpretation. Evidently, owing to their great resistance to the chemical processes attendant upon weathering, the grains of osmiridium, unlike the detrital gold, have not been dissolved and redeposited, but instead have maintained their original form and character. It is generally admitted that the gold and osmiridium were deposited simultaneously. It therefore follows, without the cogent collateral evidence, that all the precious metals of the Witwatersrand originated as detrital deposits.

The exact sources of the gold and platinum metals are not definitely known, though granitic intrusives within the Swaziland system, are known to be mineralized with gold, tin, and columbite, Most geologists familiar with these deposits believe that these metals were transported for a long distance from bedrock sources to the northwest or north-northwest that are now either eroded or overlapped by younger geological formations. It is certain that these bedrock sources are not directly related to the platinum-bearing intrusives of the Transvaal, as the former are millions of years older than the latter. Probably the noble metals of the Witwatersrand were contained in sediments that were transported by and deposited from a large river that built a delta close to the sea.

CHEMICAL COMPOSITION

Data are shown in table 22 on the composition of these platinum metals, which appear to be mainly osmiridium (iridosmine). It must be stated, however, that these chemical data are inferred from the records of production, and are not based directly upon chemical analyses. It is believed by Wagner (1929, p. 36–37), that two or more alloys are present, and as this is probably true, it follows that the cited compositions of the osmiridium are analogous to chemical analyses of bulk samples of unseparated alloys, like most analyses of placer samples.

TABLE 22.—*Composition, in percent, of osmiridium from Witwatersrand*

[N.D., no data]

	Platinum	Iridium	Osmium	Ruthenium	Rhodium	Ruthenium and rhodium	Palladium	Total
A_1	13.02	32.00	37.24	17.21	0.53	....	N.D.	100.00
A_2	9.64	33.29	42.57	14.28	.22	....	N.D.	100.00
A_3	7.57	37.54	42.46	12.19	.24	....	N.D.	100.00
A_4	6.70	39.16	43.46	10.51	.17	....	N.D.	100.00
A_m	9.19	35.56	41.46	13.50	.29	....	N.D.	100.00
B_1	15.70	36.55	41.36	N.D.	N.D.	15.41	N.D.	....
B_2	4.48	22.07	24.82	N.D.	N.D.	10.29	N.D.	....
B_m	11.82	34.35	38.77	N.D.	N.D.	15.06	N.D.	100.00
C	13.43	33.13	37.28	15.63	.53	....	N.D.	100.00
D	12.67	32.58	37.09	15.82	.84	....	N.D.	100.00
E_1	18.90	40.55	44.60	16.83	1.04	....	N.D.	....
E_2	3.80	21.33	24.13	8.73	.34	....	N.D.	....
E_m	12.68	34.29	38.10	14.17	.76	....	N.D.	100.00
Weighted mean	12.86	33.54	37.87	15.03	.70	....	N.D.	100.00

A_1, A_2, A_3, A_4, and A_m. Four analyses and their mean value that show variations in composition at four different mines (Wagner, 1929, p. 37).
B_1, B_2, and B_m. Two analyses and their mean value that show the maximum (B_1), minimum (B_2), and mean (B_m) compositions at most of the large mines (Wagner, 1929, p. 38).
C. The mean composition of the platinum metals sold in a period of 10 years during the period 1925–34 (Imperial Institute of Great Britain 1936, p. 60).
D. The mean composition of the platinum metals sold in a period of 17 years within the interval 1927–49 (U.S. Bureau of Mines, Minerals Yearbooks 1928–50).
E. Two analyses and their mean value that show the maximum (E_1), minimum (E_2), and mean (E_m) compositions of the platinum metals for 15 years prior to 1950 (U.S. Bureau of Mines, Mineral Yearbooks, 1950).

The bulk composition of the platinum metal of the Witwatersrand is shown in table 22. Omitting A_1, A_2, A_3, A_4, B_1, B_2, E and E_2, and weighting A_m, B_m, C, D, and E_m respectively at 4, 2, 10, 17, and 15, the weighted mean of the five metals are found to be as shown in table 22. The individual analyses conform fairly well

for iridium, osmium, and ruthenium, the three major constituents, but for platinum some significant differences appear. The tenors of osmium are consistently greater than those of iridium by values ranging from 2.75 to 9.28 percent, with an average value of 4.46 percent. Hence, this product may be called iridosmine, if use is made of that term. Ruthenium, which commonly occurs with osmium, shows relatively consistent values. The values of platinum, however, range between limits of considerable magnitude, from 4.48 to 18.99 percent. This range suggests that a part of the platinum is alloyed with osmiridium, but that another part may be constained in a minor alloy of platinum that contains considerable iridium but little osmium. Palladium is not shown in these analyses, possibly because its tenor is of the order of mere traces. The ratios of the two postulated alloys could be learned only by determining the composition of one of them.

CAPE OF GOOD HOPE PROVINCE

Platinum has been found in widely separated areas in the Cape of Good Hope province, but only one of these deposits appears to have any possible significance. The recorded localities are as follows:

1. Dike in altered dolerite, near Cradock.
2. Dike in weathered dolerite and in derived eluvial and alluvial beds near Cala, about 80 miles north of Queenstown.
3. Ocherous shale of the Witteberg series of the Karroo system, near Grahamstown.
4. Small bodies of basic and ultrabasic rocks near Tabankulu, in the district of Griqualand East.
5. A large sill of basic and ultrabasic rocks in Beaufort volcanics of the Karroo system, near Insizwa, district of Griqualand East.

The Insizwa deposit appears to be the most promising of these. According to du Toit (1911) and Wagner (1929, p. 255), this sill has a length of about 12 miles, dipping everywhere toward its center, and thus it simulates a lens-shaped body with a major axis that trends approximately north. This intrusive is mainly gabbro and norite, differentiated to yield at its base a thin sheet of fine-grained perknitic dunite, or picrite. The platinum-bearing minerals occur in the picrite, either in disseminated form, or in veins and tabular masses of massive sulfide ore. The sulfides include pyrrhotite, pentlandite, cubanite, and chalcopyrite, with smaller amounts of bornite, niccolite, and sphalerite. The average tenor of platinum metals, on the basis of exploration so far done, is between 0.025 and 0.05 ounces per ton of ore. The best available information indicates that palladium greatly predominates over platinum. Considerable exploratory work was done on this deposit in 1962, by a large South African mining company.

REPUBLIC OF THE CONGO (KATANGA)

The province of Katanga, in the east-central part of the Republic of the Congo (formerly the Belgian Congo), and the adjacent part of Zambia (formerly Northern Rhodesia) have large deposits of copper and copper-cobalt ores from which significant amounts of the platinum metals, as well as gold, iron, nickel, lead and zinc are being recovered as byproducts. The total output of platinum metals from electrolytic refineries, in the period 1930–58, according to Quiring (1962, p. 97) was about 52,760 troy ounces, with a maximum output in 1936 of about 15,740 ounces.

The copper and copper-cobalt mines lie within a parabolic belt with a northern axis and a total length of about 750 miles. The average width of the belt is about 35 miles. Most of the deposits are in Katanga and adjacent parts of Zambia. Seventeen lodes of copper and 10 lodes of copper-cobalt lie between lat. 10° and 14° S., and between long. 24°30′ and 29°30′ E. Four other copper lodes occur farther to the southeast. The production data on platinum metals from these mines, as given by Quiring (1962, p. 97), establish a platinum: palladium ratio of 1:4.

RHODESIA

Platinum was found in 1914 in a cobalt-nickel-bearing chromite in the Selukwe district, between Gwelo and Fort Victoria, and in 1918 in a hematitic gossan of dunite near Indiva, about 15 miles east of Gwelo. These and other occurrences of the platinum metals, however, attracted little attention until after the discovery of platinum deposits in the Lydenburg district. Thereafter intensive prospecting was done in Rhodesia on the Great Dike (Great Dyke), an elongate mass of ultrabasic and basic igneous rocks which intrudes the granite that is the principal bedrock of the eastern half of Rhodesia. The Great Dike stretches continuously in a nearly straight line, trending S. 15° W. for about 320 miles from the headwaters of the Masingua River to the headwaters of the Bubi River. At its northern end, it terminates in a hook-shaped configuration, and beyond its southern end, it continues in intermittent outcrops for an additional 50 miles. The width ranges from 2 to 7 miles, with a mean width of about 4 miles. The layered sheets of this intrusive dip at gentle angles from both sides toward its center. This dike has been called a lopolith, but its structure and genesis have not been definitely proven.

The petrographic succession of rocks, according to Swift (1961, p. 39), consists of a principal basal mass

composed of layers of pyroxenite and serpentinite. A drill hole at Wedza, bored to a depth of 5,000 feet, showed that the deeper part of this basal mass is entirely dunite, for which reason the surficial serpentinite is attributed to the effects of meteoric rather than magmatic waters. Small xenoliths of granite afford proof of the intrusive origin of the dike. Above the pyroxenite and serpentinite is a layered minor succession of gabbro and norite, with smaller amounts of pyroxenite, which therefore constitute the central part of the synclinal igneous structure.

Two types of platinum-bearing ores have been found in the Great Dike. One consists of stratiform seams of chromite in the serpentinite, ranging in thickness from 4 to 6 inches, with a maximum recorded thickness of 14 inches. From five to 10 such seams crop out in different areas. They appear to be of no economic significance. The principal ores occur in a sheet of pyroxenite which lies 20 to 60 feet below the base of a feldspar-rich norite. These ores have been found at three principal localities. The most important of these lies in the Belingwe district, near the southern end of the intrusive, and includes the well known Wedza mine, about 15 miles west of Shabani. This deposit, which consists of a large volume of oxidized ore in pyroxenite, occurs in a reef 8 to 10 feet thick, of which the uppermost 3 to 4 feet showed tenors in platinum of 0.15 to 0.20 ounce per ton of crude ore. This property was mined in the period 1926–28, and 1,338 tons of concentrates, with platinum tenors ranging from 15 to 258 ounces per ton, were shipped to London. An examination of these concentrates proved the presence of minute octahedra of sperrylite and very small flattened crystals of cooperite, which are believed to be enclosed in iron-copper-nickel sulfides.

A second area is the Makwiro platinum field, about 165 miles north-northeast of the Wedza mine and about 18 miles west-southwest of Norton. The platinum at this locality occurs in a pyroxenitic sheet of the Merensky type, which lies about 30 feet below the feldspar-rich norite. The ore contains iron and copper minerals and is irregularly distributed, with a maximum tenor in platinum metals of 0.15 ounce per ton. A third area is in the Selundi Hills, about 45 miles north-northeast of the Wedza mine and a few miles east of Selukwe.

The Great Dike has been shown by Cousins (1959, p. 186–188) to be merely one of a chain of basic and ultrabasic intrusives that lie approximately along a straight line that trends S. 20° W. from a short distance south of the Zambesi River, in Rhodesia, nearly to the Orange River, a distance of about 1,000 miles. This line passes through the Bushveld igneous complex west of Potgietersrust, and it may extend south of the Orange River to some of the occurrences of basic and ultrabasic rocks in the Cape of Good Hope Province. Cousins believes that this line marks the position of a fracture in the crust of the earth that may extend to a great depth.

ETHIOPIA

Platinum was first produced in Ethiopia by Europeans in 1925, but platinum is known to have been purchased long before that date by itinerant traders, who probably smuggled it through the Sudan into Egypt. From 1927 to 1940, Ethiopia was a rather important producer of the platinum metals, but in recent years the output has greatly diminished. Quiring (1962, p. 93–94) has estimated that the total output, from 1926 to 1959 was about 90,200 troy ounces, with a maximum production of 8,230 ounces in 1940.

Platinum was produced in the early years from two general districts, in the valleys of the Didessa and Bir Bir Rivers, and a declining production indicates that no new discoveries have been made and that these remain in the two principal districts. Information is lacking on the Didessa district, but the Bir Bir district was studied by Duparc and Molly (1927), whence come the only geographic and geologic data. The province of Wollega lies west of the province of Shoa, south of the province of Gojjam, and has an area of about 30,000 square miles. Wollega includes some smaller districts, whose names are no longer recognized. The Bir Bir River flows generally south-southwestward to the Baro River, which empties into the Sobat River, which is an eastern tributary of the Bahr el Abiad (White Nile) River; the Didessa River, against which the Bir Bir heads, flows northwestward into the Bahr el Azraq (Blue Nile) River. This platinum field is in a remote area, about 220 miles west-southwest of Addis Ababa, and is difficult to reach from Addis Ababa, or from the head of navigation on the Baro River.

The productive area in the Bir Bir district is near Yubdo, which is on the west side of the Bir Bir River, on a plateau in which this stream is entrenched. This plateau consists of two well-defined ridges, the Yubdo ridge trending north and the Sodo Ridge trending northwest. The Yubdo ridge lies between the Bir Bir and Kobe Rivers, and its northern extremity is separated from the Sodo Ridge by a western tributary of the Bir Bir River, called the Alfe River. The plateau consists of a basement of ancient crystalline rocks, with may silicic and a smaller number of basic intrusives, mantled by basaltic, trachytic, and other volcanic rocks of Tertiary age. To the east, a sequence of Meso-

zoic rocks lies between the crystalline rocks and the Tertiary volcanics. The Yubdo and Sodo ridges consist mainly of dunite bordered by pyroxenite, which in turn is bounded discontinuously by gabbroic rocks. At some places where dunite forms the crests of these two ridges, there occurs a well-indurated brownish quartzite, which has been produced by the silicification of dunite. This rock, which contains 9 percent Fe_2O_3 and 1 percent Cr_2O_3, has been called a birbirite by Duparc and Borloz (1927, p. 137–139). This weathered rock extends below the surface to a depth of 10 to 15 feet, and contains platinum, of which an analysis is later presented. Much of the platinum in this field, however, is recovered from deposits of red clay that mantle the tops and slopes of the hills over an area of about 100 square miles. This represents residual and eluvial material derived from the ultrabasic and basic rocks. Another part of the platinum is recovered from gold-platinum placers in the valleys of the Bir Bir and Didessa Rivers and their tributaries.

Data relating to the character of the platinum are lacking, nor are the accessory minerals of the concentrates recorded. It is reasonably certain, however, that chromite is one of these, as the platinum metals resemble closely those from the Urals. The largest nugget found is said by O'Neill and Gunning (1934, p. 134) to have come from the Didessa River, or one of its tributaries, and to have weighed 0.48 troy ounce. Two analyses of the platinum metals are available. One, designated below as A, was made by Duparc of a cleaned sample from the birbirite, and this was republished by The Imperial Institute of Great Britain (1936, p. 96). A second analysis, designated as B, was made by Johnson, Matthey and Co., Ltd. These two analyses, and their mean value (C), recomputed to total 100 percent, are as follows:

Analyses, in percent, of platinum metals, Bir Bir district, Ethiopia
[N.D., no data]

	A	B	C
Platinum	95.82	94.60	95.21
Iridium	.99	.84	.92
Osmium plus iridium	1.70	3.48	2.59
Ruthenium	N.D.	N.D.	.85
Rhodium	.90	.80	N.D.
Palladium	.59	.28	.43
Total	100.00	100.00	100.00

SIERRA LEONE

Platinum was first discovered in Sierra Leone in 1926, and placer mining began in 1929 and continued until 1957, after which no production has been recorded. The total output from 1929 to 1957 is estimated by Quiring (1962, p. 93–94) to have been about 5,560 troy ounces, with a maximum production of about 740 ounces in 1935.

The productive area has been confined to a small peninsular area that extends from Freetown, on the Atlantic coast southeastward for about 25 miles, with a maximum width of 8 or 9 miles. This peninsula is bounded on the northeast by an inlet from the ocean, on the south by Yawri Bay, and on the west by the Atlantic Ocean. The entire peninsula is a rugged and densely forested mountain mass that rises to an altitude of 3,000 feet, and is deeply dissected by numerous mountain streams with high gradients and boulder floors. Mining is impracticable during the wet season, and therefore is carried on from October to June.

The peninsula consists of a large basin-shaped body of basic and ultrabasic rocks, of which the western part, adjacent to the ocean, has been removed by erosion. This is indicated by the fact that the same rocks crop out on Banana Island, which lies offshore to the southwest. These rocks have a well-defined primary banding of stratiform character. The lower part of the intrusive mass is mainly olivine norite or troctolite, whereas the upper part is somewhat less basic. Two large lenticular sheets of coarse-grained anorthosite and anorthositic gabbro have been recognized, and these are believed to be the sources of the platinum metals, as all streams which dissect them have platinum-bearing gravels.

The platinum metals recovered from the placers are coarse grained, and numerous nuggets weighing between 0.25 and 0.52 ounce have been found. One nugget weighed 1¼ ounces. The larger nuggets are invariably waterworn, but small angular grains of crystalline character are also present. A part of the platinum is ferromagnetic. The principal minerals of the concentrates are titaniferous magnetite and ilmenite, and platinum is found adhering to grains of ilmenite. One chemical analysis of the platinum has been published by The Imperial Institute of Great Britain (1936, p. 42). This analysis, recomputed to total 100 percent, is platinum 93.14, iridium 1.01, osmium plus iridium 2.82, rhodium 1.29, palladium 1.74, ruthenium not determined. The absence of osmiridium is indicated.

A geologic exploration has recently been made of this district by a large South African mining company, to determine if possible the bedrock sources of these platinum metals. This work failed in its principal objective, and led to an interpretation that the platinum metals occur in widely disseminated grains, which over a very long period have been concentrated by weathering and erosion to form the present placers.

UNION OF SOVIET SOCIALIST REPUBLICS
HISTORY AND PRODUCTION

Platinum was discovered in the stream gravels of the Ural Mountains, according to Sobolewsky (1835), in 1822, and production of the platinum metals began in 1824 and has continued to the present time. At the outset, ruthenium and palladium were not recognized, and even the analyses shown in table 23 do not mention the presence of ruthenium. These placers were slowly depleted, and a search was begun for platinum lodes. Primary ores were found in the Urals in 1890, but proved not to be of the kind that yielded large workable mines. Sometime in the thirties, however, lode deposits of nickel-copper ores containing the platinum metals were found in northwestern Siberia, in the vicinity of Noril'sk. As a result of the development of these and other lodes, and notwithstanding the lessened output from the Uralian placers, the platinum production of Russia has been increasing for some years. Other lodes and some smaller placers have also been found in the U.S.S.R. Among these are the lodes of the Petsamo district, a part of which formerly belonged to Finland.

The production of platinum metals by the U.S.S.R. is approximately known, but it is impossible to separate the placer from the lode outputs. According to the figures presented by Quiring (1962, p. 93–94), the production from 1823 to 1960 has been 12,886,000 ounces, to which should be added 5,300,000 ounces credited to the U.S.S.R. in the years 1961–65. The total production is therefore about 18,186,000 ounces up to and including 1965, which is about 42½ percent of the world's production. A maximum output of placer platinum, amounting to 241,125 ounces, was made in 1912. The largest production, coming from both lodes and placers, was 1,700,000 ounces and was obtained in 1965.

URAL MOUNTAINS
LODES

Primary ores of the platinum metals were found first in the Nishniy-Tagil district, of the Ural Mountains. These consisted of relatively small segregates of chromite, which locally contained accumulations of the platinum metals. These ores have been investigated mainly by Inostranzev (1893), Karpinsky (1926), Duparc and Tikonowitch (1920), Zavaritsky (1928), Vysotsky (1933), and by Betechtin (1930, 1935, 1961). In addition to the publications cited, Betechtin published a series of papers in the Russian language, with no abstract in any other language.

The Ural Mountains lie along the western margin of a belt of basic and ultrabasic rocks, mainly of gabbroic character, which have invaded a country rock consisting of Paleozoic sedimentary rocks and older crystalline schists. Figure 4 shows the localities of dunite in the Ural Mountains. The ultrabasic rocks occur in 11 ovaloid dome-shaped masses, with elongations roughly parallel to the axis of the Ural Mountains. These extend over a distance of about 300 miles, between lat 56° and 60°30′N., but the more important ones lie within a range of 190 miles. These rocks extend from a point 60 miles N. 30° W. of Sverdlovsk northward to about 20 miles N.15° W. of Severovral'sk, as shown in figure 4. The ultrabasic masses range in length from 4,000 feet to 6½ miles and have areas from 300 acres to about 12 square miles.

The principal platinum-bearing rocks are dunite, peridotite other than dunite, and pyroxenite, of which dunite is the most important source rock. The dunite is rarely completely unaltered but shows instead various stages of serpentinization. The unaltered dunite consists almost entirely of olivine in a panidiomorphic fabric, but includes disseminated grains, pockets, stringers, and lenses of chromite. Native platinum is rarely visible in the average dunite, even under the microscope; but where present in ore deposits, it is commonly intergrown with chromite, rarely with olivine. The platinum metals, which include osmiridium, occur generally as minute isolated globules or crystalline grains; but as later described, large segregates of primary platinum have been found. Duparc and Tikonowitch (1920) estimated from the amounts of alluvial platinum metals recovered from the placers that the average tenor of these metals in the dunite of the Nishniy-Tagil area was about 0.13 grain per cubic yard. Obviously, only significant concentrations could be of economic value.

The pyroxenites, which are rather constantly associated with dunite, are classified by Duparc and Tikonowitch as pyroxenite proper and koswite. The pyroxenite consists dominantly of monoclinic pyroxene, but includes also some olivine and accessory magnetite. The koswite (magnetite peridotite) is a more basic rock that contains olivine and magnetite, together with some hornblende. Hornblendite is also present. The gabbros, of which there are numerous varieties, are either barren of platinum metals or have exceedingly low tenors, amounting to mere traces.

The dunites of the Urals were studied in great detail by Duparc and Tikonowitch (1920), and later by Zavaritsky (1928). These writers agree that the ultrabasic rocks of the Urals are segregates from, and not intrusives into, the gabbros. There are, however, a large variety of dike rocks which intrude both the basic and the ultrabasic rocks. The ultrabasic rocks were also affected by still later processes, such as the formation of minerals in miarolitic cavities, later by

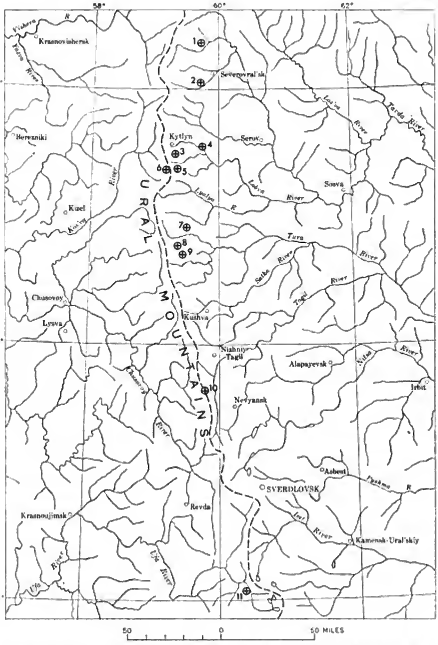

FIGURE 4.—Dunite localities in the Ural Mountains. 1, Daneskin-Kamen area, drained by the Sosva and Souprela Rivers and their headwater affluents. 2, Gladkaïa-Sopka area, drained by the Wagram River and its tributary the Travianka River. 3, Kanjakowsky area, drained by the Severney-Jow and the Pouloudniewaïa Rivers. 4, Garewaïa area, drained by the Garewaïa and the Jow Rivers. 5, Koswinsky-Kamen area, drained by the Kytlyn River and its headwater tributaries. 6, Sosnowsky-Ouwal area, drained by the Tilaï River and its headwater tributaries, and the Earkovka River. 7, Kameuouchky area, drained by the Niasma River and its headwater tributaries and the Sokolka River. 8, Weressowy-Ouwal area, drained by several headwater tributaries of the Iss River. 9, Swetli-Bor area, drained by the Iss River, and one of its tributaries called the Kossia River. 10, Tagil area, drained on the European side by the Wyssim, Syssim, and Martian Rivers and their affluents and on the Asiatic side by the Bobrowka and Tschauch Rivers and their affluents. 11, Omoutnaïa area, drained by the Omoutnai River, and a headwater tributary of the Tschoussowaïa River.

serpentinization, and still later by the formation of carbonates and other minerals of supergene origin.

The dunite of the Nishniy-Tagil district is the largest intrusive of this type in the Urals and may be regarded as typical of the others. This mass, as described by Betechtin (1961) and as illustrated in figure 5, includes a discontinuous band of antigorite-serpentinite along its western side and is surrounded by pyroxenite (diallageite). The transition from dunite to pyroxenite is characterized by a rock of intermediate character called tilaite, which is composed of diopside, augite, orthopyroxene, olivine, and basic plagioclase feldspar. Eastward from the pyroxenite are successive gabbro, diorite (locally syenite), quartz diorite, and granite. All these rocks pass gradually into one another without sharp boundaries, and suggest complementary species resulting from magmatic or gravitative differentiation.

The dunite of the Nishniy-Tagil district was thought originally to represent a batholith, but it was later proved by Zavaritsky to be a relatively thin laccolith dipping gently eastward. This conclusion was established by gravimetric measurements, which showed that the dunite nowhere extended below a depth of 1.5 kilometers. Later, a drill hole, which was bored to a depth of 600 meters, showed no serpentinization below a depth of 450 meters. This was interpreted to mean that olivine, because it is denser than serpentine, had a superior stability at greater depth. Of possible interest with regard to genesis is the fact that a gas composed of hydrogen, nitrogen, oxygen, and the inert gases was discharged from this borehole for 2 weeks.

The platinum metals of the Nishniy-Tagil district occur within the dunite in irregular masses of chromite, of which about 600 masses have been found. Many of these, however, contain little or no platinum. Generally, chromite occurs as an accessory mineral in the dunite, in amounts ranging from 1 to 2 percent. It is believed by Betheehtin that there existed in the silicate magma an unstable chemical compound of chromium, iron, and platinum, together with fluid components or mineralizers, which were gradually dissipated with falling temperature. The progressive disintegration of this chemical compound produced several other types of chromite deposits, which have different characteristics.

The first and earliest type of ore deposit was formed by direct crystallization from the dunitic silicate magma. During this stage, the chrome ore crystallized in zones and irregular nonlinear aggregates that are characterized by indistinct boundaries and an absence of other accessory minerals. These deposits apparently were entirely of magmatic origin. In a second stage, the chromite accumulated in bodies which, though not entirely regular in outline, were distinct and sharply delineated from the adjacent dunite. These deposits were vein-like and miarolitic, and many of them showed bordering halos that contained chrome-garnet, chrome-chlorite, and dioside, rarely sulfides. These ores were found also to be related to crosscutting coarsely crystalline dikes that contained enstatite, diallage, and other minerals of a pegmatitic character. Such ores were therefore considered probably to be both hydrothermal and pegmatitic and were believed to be contemporaneous with an early stage in the decomposition of the postulated chrome-iron-platinum compound.

The third stage in the crystallization of the chromite and platinum metals yielded the more significant ore deposits. This stage apparently marked the final disintegration of the chrome-iron-platinum compound and took place when the dunite was partly congealed and was being subjected to structural dislocations. These conditions resulted in the formation of a brecciated but unaltered dunite with irregular cavities, which were filled with the chrome-iron-platinum compound that still retained a part of its fluid components. These deposits are sharply defined and are considered to be hydrothermal in origin. They are characterized by an abundance of accessory minerals such as chrome-garnet, chrome-diopside, and chrome-chlorite. Most of the chromite-platinum lodes of the Urals are believed to have been formed during this stage of crystallization. They range in length from 1 to 400 feet. Three such lodes, in the Nishniy-Tagil district, are called the Gosshakhta, Aleksandrovskii Log, and the Krutoy Log lodes. In the Krutoy Log property, a mass of high-grade chromite-platinum ore at the top of the ore body extended in one adit for a distance of 2 meters. From this deposit was recovered about 965 ounces of native platinum metals, of which the largest mass weighed 13¾ troy ounces. Unfortunately such deposits were few and widely separated, and none of the numerous chromite ore bodies has been developed into a large producing mine.

A fourth stage in the history of mineralization, contemporaneous with the final solidification of the dunite, resulted in serpentinization, together with the formation of native copper, nickel-iron, magnetite, calcium and magnesium carbonates, brucite, ferrobrucite, and related minerals. This late hypogene process produced only small amounts of platinum and insignificant amounts of iridium. A final stage was marked by exogenic processes whereby supergene solutions, acting upon the olivine, produced iron and magnesium hydroxides and carbonates.

FIGURE 5.—Nishniy-Tagil dunite massif. (From Betechtin, 1961.)

Zavaritsky (1928, p. 37) has presented 15 chemical analyses of primary platinum metals collected from different parts of the Nishniy-Tagil district. These, recomputed to total 100 percent, are shown in table 23. Like all Russian analyses seen by the writer, a part of the iridium is included with osmium, and ruthenium has not been determined. Two mean values have been computed, one including copper, nickel, and iron, and the other without these elements. The ranges in the percentages of copper, nickel, and iron, are respectively 0.50 to 11.41, 0.30 to 3.70, and 10.76 to 15.55. It is uncertain whether these three base metals represent dross, or impurities resulting from unseparated heavy minerals, or both.

TABLE 23.—*Analyses, in percent, of primary platinum, Nishniy-Tagil district*

[Based on data from Zavaritsky, 1928, p. 37., N.D., no data]

No.	Platinum	Iridium	Osmium plus iridium	Rhodium	Palladium	Copper	Nickel	Iron	Total
1	72.43	----------	4.22	[1] 6.93	N.D.	0.87	----------	15.55	100.00
2	74.37	7.14	5.85	.70	.18	.50	0.50	10.76	100.00
3	78.50	1.54	8.87	N.D.	N.D.	N.D.	N.D.	11.09	100.00
4	72.49	7.01	5.75	1.00	.20	2.00	.30	11.25	100.00
5	73.56	1.58	.52	.63	.06	8.62	----------	15.03	100.00
6	74.88	1.83	4.67	.54	Tr.	4.81	.95	12.32	100.00
7	72.01	1.42	3.54	.23	.20	8.17	1.54	12.89	100.00
8	76.27	3.83	3.62	.60	.12	2.94	.81	11.81	100.00
9	74.45	1.57	5.03	1.00	Tr.	5.31	1.01	11.61	100.00
10	73.66	4.10	2.78	.43	.18	5.13	1.05	12.67	100.00
11	74.69	1.80	2.42	.74	.05	4.06	3.70	12.54	100.00
12	55.64	1.08	14.97	.36	.15	11.41	1.45	14.94	100.00
13	69.84	4.10	9.49	.74	.11	3.47	.40	11.85	100.00
14	68.67	6.20	8.21	.98	.10	3.49	.27	12.08	100.00
15	72.61	4.74	4.54	.54	Tr.	4.67	.93	11.97	100.00
Mean	71.93	3.46	5.62	.65	.14	4.63	1.07	12.50	100.00
Mean	87.94	4.22	6.88	.80	.16	----------	----------	----------	100.00

[1] Iridium plus rhodium.

A comparison of the amounts of platinum metals in the Uralian lodes and placers can be made. The means of those that represent the placers of the Nishniy-Tagil district, computed free of impurities, are given in analysis C_2 that is shown in table 24, on page 59 of this report. Comparing the mean values of Zavaritsky's analyses with analysis C_2, it will be seen that the tenor of platinum in the former is about 4 percent less than in the latter, that the total iridium plus osmium is about 4⅓ percent larger, that rhodium is about 1 percent less, and that palladium is about 0.5 percent smaller, that is, only about a fourth as large. Differences of the same order of magnitude result by comparing the mean of Zavaritsky's analyses with analysis G_2, of table 24, which represents the mean product from all the dunitic areas of the Urals. These differences may be explained in several ways, of which two will be stated. If the principal platinum alloy is intergrown with osmiridium, a possible inference might be that the placer samples represent metals that were eroded from apical horizons in the lodes, whereas Zavaritsky's samples represent metals in different proportions that are characteristic of lower horizons in the lodes. If, on the other hand, the placer samples represent a detrital mixture of two distinct alloys, coming perhaps from different areas in the drainage systems, the discrepancy may be more readily explained by the assumption that the principal platinum alloy was mixed with osmiridium, in approximately a ratio of 20:1. The true explanation may be much more complex than the two above cited, and from studies in progress on the platinum metals of the Goodnews Bay district, Alaska, it seems that other interpretations are probable.

PLACERS

SOURCES

The Uralian platinum placers are coextensive with the bodies of ultrabasic rocks of the Urals, as heretofore described. These rocks, and their resulting placers, are divided by Duparc and Tikonowitch (1920, p. 41–43), into 11 dunitic and five pyroxenitic centers. The dunitic centers and the principal rivers that drain this stretch of the Ural Mountains are shown in figure 4. The headwater tributaries, where most of the placers were mined, cannot be shown on a map of such a small scale, but most of these headwater streams are given in the figure caption. Figure 4 shows that eight of these dunitic centers are on the Asiatic side of the Urals, two are on the European side, and one, the Tagil area, is on both sides. The richest platinum placers of the Urals were in the Tagil area, and here the most important placers were on the European side of the divide.

Smaller amounts of the platinum metals were also eroded from pyroxenitic bedrock. Each of the dunitic areas is surrounded, or partly bordered by pyroxenite, but in addition to such sources, Duparc and Tikonowitch (1920, p. 49–50) also mention five localities where platinum-bearing pyroxenite occurs without dunite. These are not shown in figure 4 but are located as follows:

1. Tokaïsky area, which comprises a body of pyroxenite whose center lies about 14 miles S. 60° E. of the Koswinsky-Kamen dunite area.
2. Goussewi-Kamen area, about 10 miles east of the Swetli-Bor dunite area.

3 and 4. Sinaïa-Gora and Kiedrowka areas, about 24 and 15 miles respectively north of the Tagil dunite area.

5. Obleiskaya-Kamenka area, which lies directly west of the Nishniy-Tagil dunite area.

All these areas except the fifth are on the Asiatic side of the Ural Mountains.

PHYSIOGRAPHY

The physiography and hydrology of the Ural Mountains is briefly described by Duparc and Tikonowitch (1920, p. 1–6). The area is one of mature topography, and the rounded mountain tops in that part of the range where the placers occur have altitudes ranging from 1,300 to 3,500 feet. Timberline in the central Urals has a mean altitude of about 2,700 feet, so that much of the area is timbered. The western flanks of the Urals are more abrupt than the eastern flanks, which by Duparc and Tikonowitch is attributed to late tectonic disturbances. This condition is probably reflected in the character of the placer deposits. The streams on both sides of the Urals, and in large measure within the mountains, flow in silt-filled valleys through rolling country, and the water is normally clear, though the more sluggish streams are commonly stained a brownish color by dissolved vegetal matter. Most of the Urals and all the placer-bearing areas lie southwest of the regional belt of permafrost. Wisconsin glaciation, according to Suslov (1961, p. 6), extended southward in the Urals to some line between lat 59° and 60°, and as the placer fields lie between lat 56° and 60°30′, only the northern fourth of these fields was glaciated in Wisconsin time. Therefore, the placer loci 7 to 11 inclusive, as given above, are in unglaciated territory, and these include the rich placers of the Nishniy-Tagil area. The ice in the glaciated area, however, was rather sluggish, and apparently did not obliterate the placers.

DEPOSITS

The placer deposits have not been adequately described in detail, except perhaps in the Russian language. One early report that contained cross sections of numerous workings was published by Saytzeff (1897, 95 p.). This paper was written in Russian with a short résumé in German. Duparc and Tikonowitch (1920, p. 264–282) have given a classification and general description of the placers. Compiled statements have also been published by O'Neil and Gunning (1934, p. 117–121) and by the Imperial Institute of Great Britain (1936, p. 90–93). Duparc and Tikonowitch have classified the Uralian placers into three principal types, to which they have added a fourth and subordinate type. Their classification is as follows:

1. "Lojok" alluvials, which comprise residual and eluvial deposits.
2. Stream placers in the present valley floors.
3. Low terrace deposits of fluvial origin.
4. Certain higher alluvium, to which a Tertiary age was assigned.

Some generalized sections of these deposits are given.

The residual deposits consist of weathered dunitic and pyroxenitic debris, mainly the latter if pyroxenite is present, because dunite disintegrates under weathering more rapidly than pyroxenite. Most of the weathered debris is unsorted, consisting of pyroxenitic fragments in a dunitic sand, but the platinum metals tend to be concentrated toward the base of the section. The rocks are deeply weathered, and the thickness of residual and eluvial deposits may be considerable. The eluvial deposits show some sorting of materials, and grade imperceptibly downstream into the headwater fluvial deposits. Typical stratigraphic sections through the "lojoks," which range in thickness from 18 inches to 70 feet, include an ill-defined basal stratum of platiniferous sand, with a thickness of 6 inches to 10 feet, overlain by sand and rock debris with a thickness of 6 inches to 50 feet. The uppermost part of the deposits consist of turf and vegetal material with a thickness comparable to the basal layer. The thick medial stratum contains a little platinum, but the bedrock, particularly if shattered, may contain considerable alluvial platinum, so that this broken debris has to be removed and cleaned in order to obtain a high recovery. This condition, however, is more prevalent farther downstream, where fluvial action has been marked.

The stream placers range from narrow, shallow paystreaks in the headwater stretches of streams draining areas of ultrabasic rocks to much wider and thicker bodies of alluvium in the lower valleys. Duparc and

Tikonowitch give a generalized section, that illustrates apparently the placers in the upper but not the headwater stretches of some of the streams. The section consists of a lower stratum of productive alluvium, ranging in thickness from 10 inches to 5 feet of argillaceous gravel, overlain by 1 to 13 feet of gray-green to yellow porous sands and gravels, in turn overlain by 20 inches to 5 feet of brown to gray clay. The uppermost layer consists of 14 inches to 3⅓ feet of turf and vegetal material. The lower stratum is generally workable for its content of platinum metals, but the higher strata are virtually barren.

The placers in the main valleys range in thickness from 10 to 60 feet. In the valley of the Iss River, according to Purington (1899, p. 10), the thickness below the surficial layer of turf and vegetal material ranged from 8 to 24 feet. The turf, which is stripped off before mining, has a thickness of 5 to 20 feet. No sections in the lower valleys are available, but it i known that most of the platinum metals are confined to a relatively thin basal stratum, which is overlain by a thick body of barren or very low grade sand and gravel, commonly interlayered with beds of silt and clay. The surficial stratum consists of turf and vegetal material. The principal bedrock in the main valleys away from the Urals is gabbro, which is deeply weathered to clay, so that the alluvial platinum penetrates into it to a variable depth. This fact makes it necessary for the dredges to dig considerable bedrock. This platiniferous clayey bedrock is difficult to decompose by water, and thus arises a problem in high recovery of the platinum metals. Kemp (1902, p. 75) records the fact that locally there are also beds of productive gravels in the medial overburden. It is probable that the basal platiniferous gravels are buried placers of Pleistocene age, overlain by Recent alluvium, in which the later paystreaks occur.

The widths of these paystreaks, which are narrow in the headwater stretches of the streams, become very wide in the lower valleys. According to a statement by Kemp (1902, p. 70), the workable ground in the lower valleys had widths ranging from 400 to 1,600 feet and in places may have been as great as 2,500 feet. Most of these placers have been repeatedly worked, beginning in the early days with shoveling-in operations in the headwater stretches and culminating in the installation of large electric dredges. Some of the small headwater streams are still worked by hand methods, as are parts of the terrace deposits.

Some of these placers extend a long distance downstream, as for example, in the valley of the Iss River, where the paystreak was worked from the center of the Wéressowy-Ouwal dunite area downstream to the confluence of the Iss and Tura Rivers, a distance by stream of about 50 miles. Thence the paystreak continued down the Tura River for at least 50 more miles. The same conditions apply on the European side of the Nishniy-Tagil area, where the Wyssim, Syssim, and Martian Rivers had paystreaks throughout their lengths and the platinum-bearing gravels continued from their mouths down the Chusovay River, though not in a measure comparable with the deposits on the Tura River. Similarly on the Asiatic side of the Nishniy-Tagil area, the Bobrowka and Tschauch Rivers had long paystreaks.

The terrace deposits on the sides of the main streams evidently lie at no great distances above the valley floors, as it is recorded that they are flooded during periods of extreme high water. Most of the platiniferous sands at the base of the terrace deposits range in thickness from 2½ to 7½ feet, and are overlain by clay ranging in thickness from 12 to 33 feet, rarely attaining a thickness of 130 feet. At some localities, two productive strata occur in the terrace deposits, as for example on the Iss River. Type sections of these terrace deposits are as follows:

1. Brown clay (top of section), thickness 12 inches to 33 feet.
2. Productive stratum, in part pebbly, in part argillaceous, thickness 8 inches to 5 feet.
3. Barren brown clay, thickness 22 inches to 28 feet.
4. Productive stratum, generally more clayey than the upper productive stratum, thickness 7½ inches to 9¾ feet.
5. Sediments of variable character, but unstated thickness. Hence, the depth to bedrock is not known.

It is evident from these sections that the base of the terrace deposits lies far below the level of the valley floor. The widths of the terrace paystreaks range generally from 33 to 165 feet, but some of them attain widths of 500 to 650 feet. The productive sands and clays of these deposits are apparently of Pleistocene age, as they contain numerous remains of *Elephas primigenius*.

The original tenor of the platiniferous gravels and sands in the rivers draining the Urals is only of historical interest, as all the high-grade ground has been mined and deposits of far lower grade are now being worked. It is recorded that the Wyssim, Syssim, Martian, and Tschauch Rivers, which drain the Nishniy-Tagil area, had at the outset of mining some placers with tenors as high as 10 troy ounces per cubic yard, though this had diminished before the First World War

to tenors ranging from 0.01 to 0.85 ounce per cubic yard. The same conditions also applied to the placers of the Iss River and its tributaries, that drain the Wéressowy-Ouwal area, though these placers were not as high grade as those of the streams draining the Nishniy-Tagil area. It is not invariably clear whether the quoted tenors refer to the productive strata alone, though it is thought that generally this is true. Purington (1899, p. 12) stated clearly, however, that his average value per cubic yard on the Iss River, as of 1899, referred to the whole alluvial section of 10½ feet. This overall tenor was about 64 cents per cubic yard, but the platinum metals at this time had only about a third of their present value. The tenors of the ground in the lower valleys, as for example on the Tura River, are not known, but they must be approaching the value of marginal deposits that cease to be workable.

Few data are available on the character and sizes of the noble metals of the stream placers. In the headwater stretches of streams draining the ultrabasic rocks, only the platinum metals occur; but in the downstream stretches, as in the Tura Valley, the ratio of platinum to gold, according to Purington (1899, p. 11), was about 5:1. The granularity of the platinum metals, throughout the length, width, and depth of the paystreaks, has not been recorded. Some very large nuggets, however, were found in the headwater stretches of some streams, and these were especially plentiful in the Nishniy-Tagil area. The largest recorded nugget, which was recovered from a tributary of the Martian River, weighed 25¾ troy pounds. Nuggets were less common on the Iss River and its tributaries, but two large ones from the Wéressowy-Ouwal area weighed 22½ and 10½ troy pounds. Coarse gold and platinum do not commonly migrate any great distance downstream from their bedrock sources, and it is therefore inferred that the platinum recovered from the lower valley of the Iss River and from the Tura Valley must be exceedingly fine grained—a feature engendering a problem of high recovery. These long paystreaks, however, also suggest either enrichment from local bedrock, or the existence of some geologic process, such as stream rejuvenation, that would distribute the precious metals so far downstream.

CHEMICAL ANALYSES

Numerous analyses of the platinum metals recovered from the Uralian placers are available, but they are all inferior analyses in which one or more of the components are not determined or are stated in combination with some other platinum metal. The tenors in gold are given, and these must be deleted, as the native gold is free, not alloyed with the platinum metals. Some of these analyses show components designated as sand, manganese, insoluble, and loss, all of which must likewise be deleted. Where tenors in copper, iron, or nickel are stated, however, it seems probable that a major part of these are alloyed elements of the dross, and the analyses are shown both with and without them, recomputed in both analyses to total 100 percent.

Kemp (1902, p. 18–21) published 26 analyses of platinum, seven analyses of osmiridium, and one analysis of platiniridium from the Uralian placers, most of which came from the Nishniy-Tagil area. The analyses of osmiridium, which are known to have come from the vicinity of Syssertsk, were later republished by Duparc and Tikonowitch (1920, p. 189). The analyses of platiniridium, made in 1835, is omitted in computing a mean analysis, as no similar platinum alloy has been recorded from this area. The 26 samples of platinum are said by Kemp to have been nuggets, but it is not clear whether each sample was a single nugget, or an assemblage of small nuggets.

Duparc and Tikonowitch (1920, p. 237–249) published 86 analyses of platinum metals from the Uralian placers, of which 79 came from the valleys of streams that drain areas of dunite and seven from valleys that head in pyroxenite. The two principal dunitic areas are one near Nishniy-Tagil, and a second area that includes the Wéressowy-Ouwal and Swetli-Bor centers. In so far as placer platinum is concerned, it would be difficult to separate the two last-named centers, as the boundaries of their dunite masses are separated by only a mile and both are drained by tributaries of the Iss River. Platinum analyses from four of the five pyroxenitic areas are separately tabulated by Duparc and Tikonowitch (1920, p. 247). It would be desirable to present mean analyses of the platinum metals from all 16 areas, as it appears that many of these yielded platinum metals with distinct characteristics. But most of the areas have too few analyses to yield dependable mean values. Thirty-seven analyses, however, are available from the Nishniy-Tagil area, and 26 from the Wéressowy-Ouwal and Swetli-Bor areas, which are the two most productive centers. These analyses, as shown in table 24, are assembled in the seven sets.

The analyses A_2, C_2, D_2, and E_2 are surprisingly uniform in their tenors of the platinum metals and dross, departing little from the proportions shown in G_2, which is a weighted mean analysis of 168 samples from dunitic areas. The only other comparably large group of analyses, as shown on page 88 of this report, represent the metals derived from dunite at the placer mine near Platinum, Alaska. It is noticeable that the Uralian analyses show more platinum, but

TABLE 24.—*Mean analyses, in percent, of placer platinum metals, Ural Mountains*

[N.D., no data; Tr., trace]

Samples	Platinum	Iridium	Osmium plus iridium	Ruthenium	Rhodium	Palladium	Copper	Iron	Total
A_1	77.99	2.04	2.45	N.D.	2.40	0.52	1.38	13.22	100.00
A_2	91.32	2.39	2.87	N.D.	2.81	.61			100.00
B_1	2.47	56.07	33.47	4.36	2.48	Tr.	.33	.82	100.00
B_2	2.50	56.72	33.86	4.41	2.51	Tr.			100.00
C_1	77.96	2.49	2.16	N.D.	1.54	.57	2.04	13.24	100.00
C_2	92.02	2.94	2.55	N.D.	1.82	.67			100.00
D_1	83.58	1.31	3.88	N.D.	.70	.45	.68	9.40	100.00
D_2	92.94	1.46	4.32	N.D.	.78	.50			100.00
E_1	79.79	2.26	3.60	N.D.	1.11	.48	1.44	11.32	100.00
E_2	91.46	2.59	4.13	N.D.	1.27	.55			100.00
F_1	85.66	1.00	.74	N.D.	1.18	1.05	.72	9.65	100.00
F_2	95.57	1.12	.83	N.D.	1.31	1.17			100.00
G_1	79.69	2.13	3.15	N.D.	1.34	.50	1.45	11.74	100.00
G_2	91.79	2.46	3.62	N.D.	1.55	.58			100.00

Localities of cited analyses

A_1 and A_2 Mean of 26 analyses of platinum metals (Kemp, 1902), with and without the base metals.

B_1 and B_2 Mean of seven analyses of osmiridium (Kemp, 1902), with and without the base metals.

C_1 and C_2 Mean of 37 analyses of platinum metals from the Nishniy-Tagil area (Duparc and Tikonowitch, 1920), with and without the base metals.

D_1 and D_2 Mean of 26 analyses of platinum metals from the Wéressowy-Ouwal and Swetli-Bor areas (Duparc and Tikonowitch, 1920), with and without the base metals.

E_1 and E_2 Mean of 79 analyses of platinum metals from dunitic areas of the Urals (Duparc and Tikonowitch, 1920), with and without the base metals.

F_1 and F_2 Mean of seven analyses of platinum metals from the pyroxenitic areas of the Urals (Duparc and Tikonowitch, 1920), with and without the base metals.

G_1 and G_2 Weighted mean of 168 analyses of platinum metals represented by A_1, A_2, C_1, C_2, D_1, D_2, E_1, and E_2, with and without the base metals.

only half as much iridium plus osmium, as do the Alaskan analyses. On the other hand, the Uralian analyses show more rhodium and palladium than do the Alaskan analyses.

Samples F_1 and F_2, from one of the Uralian pyroxenic areas, probably represent a principal alloy of platinum containing little or no osmiridium. This is indicated by a tenor in platinum higher than those of G_1 and G_2, by the lower tenor in iridium plus rhodium, and by a distinctly higher tenor in palladium. On the other hand, analyses B_1 and B_2, as presented by Kemp, represent seven samples from the vicinity of Syssertsk, which are quite different. These show very low tenors in platinum, with nearly 90 percent iridium plus osmium and practically no palladium. Obviously such analyses represent osmiridium, with no intergrown platinum alloy of the ordinary type, though one of these seven samples contains nearly 10 percent platinum, which is sufficient to suggest a minor intergrowth of the ordinary platinum alloy.

Areal mean analyses, however, from areas of dunitic and pyroxenic bedrock do not give a complete picture of the variable character of the platinum alloys. One example of a marked variation from the cited analyses is the mean analysis of a number of placer samples from the Kanjakowsky dunite area, which shows 62.50 percent platinum and about 24.30 percent "osmiure," or combined iridium and osmium. Obviously such platinum metals represent two alloys, of which osmiridium constitutes an important, though not the major component. Still greater variations in the proportions and compositions of the component alloys are apparent in individual analyses.

The ratios between the different platinum metals have considerable interest and significance, not merely for interpreting the analyses of any one product, but also for comparing products from different regions. For the Uralian product, and in fact for most of the platinum metals elsewhere recovered, the establishment of certain useful ratios is not feasible, first because the contained iridium and osmium are usually not completely separated, and second because the content of ruthenium is rarely determined. Osmium and ruthenium occur mainly in osmiridium, and their ratio is generally nearly constant, so that the sum of these two elements may function as a fixed numerator or denominator in formulating distinctive ratios. Because platinum, iridium, and rhodium occur both in the principal alloy and in osmiridium, the ratios Pt: Os+Ru, Ir: Os+Ru, and Rh: Os+Ru are particularly significant and useful when they can be obtained. For the Uralian placers, however, all that may be safely stated is that the ratio Pt: Ir+Os+Ru is approximately 15:1, whereas for the Alaskan product the corresponding value is 6:1. The higher ratio indicates a large predominance of the principal alloy over osmiridium, and it is estimated that the ratio of these two alloys for the Uralian product is between 20:1 and 25:1, whereas the same ratio for the Alaskan product is believed to be about 12:1. This ratio, though doubtless variable in bedrock, tends to approach a constant mean value in the

placers and serves to characterize the placer platinum products in different parts of the world. The most distinctive feature of the placer platinum metals found in the Urals, Alaska, and elsewhere in the world is their low content of palladium, as compared with the platinum metals recovered from the lodes of Canada, Siberia, South Africa, and all other platinum-bearing lodes.

Other differences exist in the Uralian platinum samples with regard to their included base metals, if these are interpreted as dross. The mean of the analyses of samples from the Nishniy-Tagil area (C_2) and the mean of Kemp's analyses (A_2), thought likewise to have come from the same area, are nearly 5 percent higher in base metals than the corresponding mean analysis of samples from the Wéressowy-Ouwal area, yet both these mean analyses represent samples from areas of dunite. On the other hand, the mean analysis of samples from areas of pyroxenite shows about the same amount of base metals as the mean analysis of samples from the Wéresowy-Ouwal area. These facts suggest that none of these four means represent dross alone, but instead that all of them include undetermined amounts of extraneous impurities. It also is noteworthy that osmiridium, where it exists as a distinct alloy, constituting all the placer product, has a very low content of dross.

Few data are available regarding the heavy minerals that constitute the concentrates recovered with the platinum metals, but it is recorded that numerous such minerals have been identified. The only heavy minerals noted by the writer in the published descriptions are magnetite and chromite, though doubtless ilmenite is also present. At some places cinnabar is specifically mentioned, but this is obviously derived, not from dunite or pyroxenite, but from veins in gold-bearing granitic rocks within the basins of the Uralian streams.

NORIL'SK DISTRICT

The geographic position of Noril'sk, the general geology of the Noril'sk district, and the drainage of the surrounding country are shown in figure 6. Mount Rudnaya, also known as Rudnaya Gora (ore mountain), is the site of the original discovery of the platinum-bearing copper-nickel ores that are now being exploited. Its reported geographic position is approximately lat 69°20′ N., long 88°8′ E. A number of other similar deposits are also known in this area, of which some are being mined. Among them are the Sotnikovskol deposit, which is adjacent to Rudnaya Gora; the deposit at Mount Barjernaja, east of Rudnaya Gora; the Ugal'nyi Ruckey deposit, about 1.6 miles south of Rudnaya Gora; the Noril'sk II deposit, located approximately at lat 69°00′ N., long 89°00′ E., and the occurrence on the Rybnaja River, about 6.2 miles southeast of Rudnaya Gora. Geologic environments similar to those near Noril'sk exist also about 250 miles to the east, and continue southward from Noril'sk for 400 miles or more, so that the prospect of new discoveries are excellent. Production of platinum metals from the Noril'sk district began in 1940, and by 1947 constituted 30 percent of the annual production. This percentage has continued to increase in recent years.

The geologic environment of the ore bodies in the Noril'sk district resembles in some respects that at Sudbury, but differs markedly in others. Northwest and south of Noril'sk are numerous sedimentary formations, mainly of Paleozoic age, and southwest of Noril'sk is a large elliptic area of Triassic lavas of about 2,000 square miles. The Paleozoic rocks, from Cambrian to Carboniferous, include many limestones, but one Permian formation consists of sandstone and slate, with some beds of coal. Owing to the large area shown in figure 6, the Paleozoic sedimentary formations are not separately delineated. Numerous basic intrusives invade both the Paleozoic and the Triassic rocks, and these, though assigned an age of Carboniferous to Lower Mesozoic on Spizharskiy's (1959) geologic map, must be in part Triassic or post-Triassic in age. They are probably related genetically to the Triassic trap-rocks. The ore bodies are localized at the contacts of the intrusives with certain of the Paleozoic rocks. Shimkin (1953, p. 79) mentions as the principal loci of the ore deposits the contacts between the intrusives and Silurian limestones or Permian and Carboniferous "sands and clays." Genkin (1959) however, emphasizes the fact that the ores at Rudnaya Gora and at certain other localities are localized at the contacts of the intrusives with the coal-bearing Tungusk (Permian) coal-bearing formation.

The intrusives are mainly diabase (dolerite by transliteration from the Russian) and gabbro-diabase but include differentiated rocks such as picrite, tschenite, labradorite prophyrite, titaniferous augite diabase, and other specialized types. These intrusives differ morphologically from those at Sudbury in that they occur as large dikes, sills, and less regular intrusive bodies. The essential minerals of the undifferentiated rocks are plagioclase feldspar (commonly labradorite), augite, hornblende, biotite, and olivine, with the secondary minerals chlorite, serpentine, sericite, prehnite, and the zeolites.

The ore deposits at Rudnaya Gora are of two principal types. The high-grade ores occur as veins and lenses; the low-grade ores occur as disseminated deposits

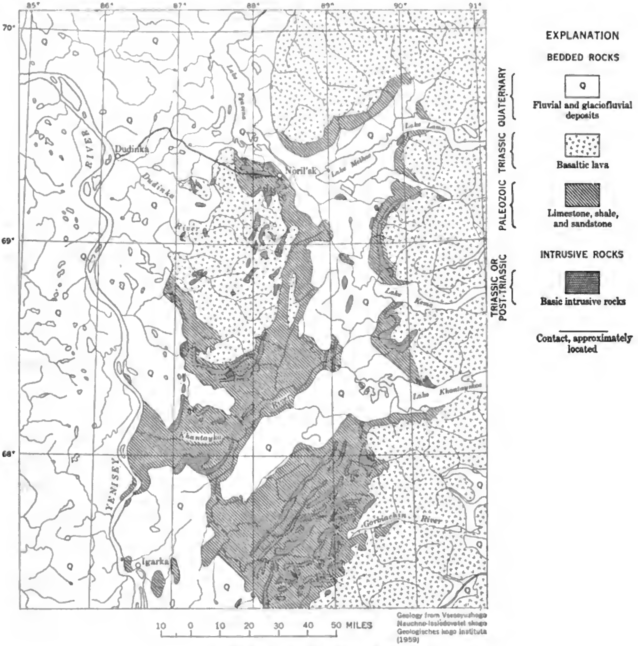

FIGURE 6.—Noril'sk district, Siberia.

in the basic intrusives. The country rock at Rudnaya Gora is sandstone and shale, which are intruded by gabbro along a fault plane striking north-northeast. One ore body, which lies in a lenticular zone in the gabbro adjacent to its footwall, has a length of about 345 feet, a width of about 200 feet, and a thickness of about 70 feet. Another ore body of lower grade consists of disseminated sulfides in the gabbro along its hanging wall and footwall.

The ore minerals of both types, according to Genkin (1959), are pyrrhotite, chalcopyrite, pentlandite, cubanite, and pyrite, with which are associated small amounts of violarite, valleriite, sphalerite, galena, polydymite, sperrylite, and other minerals and alloys of the platinum metals. In the occurrence of native alloys of palladium and platinum, these deposits differ from those at Sudbury, and are more closely related to the ores of the Transvaal. They differ, however, from the

Merensky zone in that the ores and host rocks of the latter are magmatic differentiates.

Various values have been published regarding the tenors in copper, nickel, cobalt, and platinum metals in the Noril'sk district. Quiring (1962, p.195) gives mean values for an ore lens at Rudnaya Gora of 2.16 percent copper, 1.23 percent nickel, 0.1 percent cobalt, and 0.34 ounce platinum metals per ton of ore. The tenors of the adjacent disseminated ores are given as 0.11 to 0.31 percent copper, 0.11 to 0.31 percent nickel, and 0.002 to 0.13 ounce platinum metals to the ton. For the Noril'sk area, however, Shimkin (1953, p. 147) quotes mean tenors of 0.47 percent copper, 0.31 percent nickel, 0.1 percent cobalt, and 0.07 ounce platinum metals per ton, which are about a fourth as large as those first cited. It is possible that Shimkin's figures relate to the vein deposits plus some unspecified part of the disseminated deposits that is mined. Quiring also quotes mean tenors at the Ugal'nyi Ruckey deposit as 0.65 percent copper, 0.45 percent nickel, 0.06 percent cobalt, and 0.17 ounce platinum per ton. As the ore at Ugal'nyi Ruckey is known to be of lower grade than that at Rudnaya Gora, the stated interpretation of Shimkin's values seems reasonable.

A large but undetermined part of the platinum metals at Rudnaya Gora occurs in four minerals, of which three are palladium minerals. A smaller part of the platinum metals occurs in four alloys, whose compositions have been determined by Genkin and his co-workers. These are solid solutions with variable proportions of palladium, platinum, iridium, iron, nickel, copper, tin, and silver. They are not true minerals, and many additional compositions could doubtless be discovered. The overall platinum: palladium ratio for the Noril'sk deposits is given by Genkin (1959) as 1:10. On the other hand, the platinum:palladium:iridium ratio for an ore lens at Rudnaya Gora is given by Quiring (1962, p. 195) as 3:6:1. These disparate values indicate at least that palladium is from 2 to 10 times as plentiful as platinum and therein these deposits differ from both those at Sudbury and those of the Merensky reef in the Transvaal.

The platinum minerals and alloys are rarely identified in the disseminated copper-nickel sulfides, and in this environment are believed to exist either as minute crystals, or finely divided precipitates in the sulfides, or as solid solutions replacing certain cations in those minerals. In the vein deposits, the platinum minerals exist as discrete crystalline grains in masses of sulfides or as recognizable veinlets and are believed to have been formed after the crystallization of the sulfides that surround them. This genesis is corroborated by the presence of minute inclusions of chalcopyrite, cubanite, pyrrhotite, and pentlandite within the platinum minerals. Bornite, which is not an ore mineral, has been identified as an inclusion in the platinum minerals. The ore veins generally contain seven or eight platinum minerals and alloys of very diverse composition, which exist as close intergrowths with one another, or as minute inclusions. In paragenetic association with the platinum minerals are small amounts of native gold and gold-bearing minerals.

Little has been published regarding the outlying ore deposits of the Noril'sk district. The deposit at Sotnikovskol consists of concentrations of secondary ore minerals along the bedding planes of coaly shale interbedded with marl. The ore tenors are given by Quiring (1962, p. 195) as 0.09 percent copper, 0.07 percent nickel, and 0.012 ounce platinum metals per ton of ore. The ore at Ugal'nyi Ruckey is a zone of disseminated sulfides about 95 feet thick, adjacent to the hanging wall of a sheet of diabase flanked above by a diabasic intrusive. Veinlets of ore also cut the intrusive body along its footwall. The mean tenor of the ores has earlier been stated. The ore body at Noril'sk II consists of an intrusive mass of gabbro and diabase that contains disseminated sulfides.

PETSAMO DISTRICT

The region of Pechenga-Monchegorsk, commonly called the Petsamo district, is a part of the Kola Peninsula that formerly belonged to Finland. Two well-known nickel-copper deposits, known as the Petsamo and Monchegorsk lodes, are in the district. A mass of basic intrusives of Precambrian age within this area is being intensively developed by Russia as sources of nickel, copper, and probably of platinum metals. A comprehensive report on these deposits, including their geology, structure, mineralogy, and ores, and the geochemistry of nickel, was published recently by Eliseev, Gorbunov, Eliseev, Maslenikov, and Utkin (1961, 350 p.), but this report is written in Russian with no summary in any other language. The Petsamo lode is larger and richer in copper and nickel than the Monchegorsk lode, yet no mention is made of platinum metals at either property, though they are reported to be present. The principal sulfide is pentlandite, with less chalcopyrite, and a minor amount of cobaltite. According to Shimkin (1953, p. 78), the nickel:copper ratio is about 2.3:1 and the nickel:cobalt ratio about 58:1. The tenor in nickel at the Petsamo lode is between 3.5 and 4.0 percent, and the Monchegorsk lode about 1.8 percent. The tenor in platinum metals has not been published.

MINOR DEPOSITS

Platinum has been found in bedrock and in platinum-bearing gold placers at many other Russian localities, mainly in Siberia. Such occurrences indicate a widespread distribution of platinum in bedrock, but excepting the deposits of the Noril'sk and Petsamo districts, these deposits have not been developed into workable lodes. Numerous localities are enumerated and briefly described by Quiring (1962, p. 188–199).

One of the areas mentioned by Quiring (p. 199) is the basin of Vilni River, in east-central Siberia, where platinum has been found both in bedrock and in gold placers. Seven analyses are given of the placer platinum which if recomputed to total 100 percent, with and without the base metals, yield the mean values shown in table 25. It is clear that these seven analyses represent mixtures of ordinary platinum and osmiridium.

TABLE 25.—*Analyses, in percent, of placer platinum from Vilni Basin, Siberia*

Platinum	65.11	72.46
Iridium	4.80	5.34
Osmium plus iridium	13.06	14.53
Ruthenium	2.31	2.58
Rhodium	3.93	4.37
Palladium	.65	.72
Iron	9.68	--------
Copper	.30	--------
Nickel	.16	--------
Total	100.00	100.00

Another area of some interest mentioned by Quiring (p. 192–193) is in the valleys of Timpton and Zeya Rivers, Amur Province, southeastern Siberia, where platinum-bearing gold placers occur. Quiring presents four analyses, of which two represent crude platinum, one represents ferroplatinum, and one represents a nonmagnetic iridium-rich alloy. The means of these four analyses, with and without the base metals, recomputed to total 100 percent are shown in table 26. This mean analysis indicates the presence of considerable osmiridium in these placers. It is also of interest that the concentrates recovered with these platinum metals consisted of sperrylite, magnetite, ilmenite, garnet, and zircon. An analysis of this sperrylite is given in table 8, analysis C.

TABLE 26.—*Analyses, in percent, of placer platinum of Timpton Valley*

Platinum	54.30	59.30
Iridium	18.33	20.02
Osmium and iridium	13.13	14.34
Ruthenium	1.47	1.61
Rhodium	4.12	4.50
Palladium	.22	.23
Iron	8.14	--------
Copper	.29	--------
Total	100.00	100.00

Other localities where the platinum metals have been found in bedrock, mainly in Asiatic Russia, are given in a list presented under the description of the placers. Most of these are predominantly gold placers, but obviously platinum-bearing bedrock must be present at these localities, though no descriptions of the lodes are available.

COLOMBIA

HISTORY AND PRODUCTION

The discovery of platinum in Colombia has already been described, and the early years of mining, starting in 1778, have also been mentioned. The history of placer mining subsequent to 1778 is not known, but for a hundred years much work was done by primitive methods. In the latter part of the 19th century, however, companies entered the field to work these deposits on a larger scale. One of the earlier attempts at large scale mining was made in 1882, in the province of Antioquia, on the Nechí River, a tributary of the Cauca River, which flows via the Brazo de Loba River to the Magdalena River. Platinum-bearing gold placers were also found in 1917 on the Caseri River, a tributary of the Nechí River.

Dredging began on the Nechí River sometime before 1900, and there remains today the wreck of an old French dredge that was operating as early as 1903. One of the dredges now operating on the Nechí River has been in continuous service since 1910. Several companies originally operated dredges on the Nechí River, but these were gradually taken over by a Canadian company, called Pato Consolidated Gold Dredging, Ltd., which is one of the largest placer mining concerns in the world. As of 1964, 67 percent of the stock of this company is owned by the International Mining Corp. Seven Pato dredges are now operating on the Nechí River downstream from Zaragoza. All this work, however, is mainly gold placer mining, as the annual output of platinum from these dredges does not exceed 15 ounces. This is significant merely because it shows a continuity in the occurrence of platinum over many miles of territory.

Platinum metals occur at many localities along and close to the Pacific Coast, from Panama to Ecuador. The most important of these deposits is on the Telembi River, a tributary of the Patía River, about 40 miles northeast of the Colombia-Ecuador boundary lines, in the province of Nariño. Gold and platinum have been found in the valley of the Baudó River in the western

part of the province of Chocó, but no deposits of economic value appear to have been located. Gold and platinum also occur along the Pacific beaches from Buenaventura southwestward at least as far as Ecuador; and in the provinces of Valle del Cauca and Cauca, placers have been found and worked on a small scale on a number of streams that flow directly to the Pacific Ocean. The principal of these, named from north to south, are the Raposa, Yurmanangul, Micay, Timbiqui and Guapi Rivers, but these placers have yielded only small amounts of the platinum metals. Still farther south, platinum-bearing gold deposits have been reported in the valleys of the Boyota, Cachabi, Uimbi, and Cayapas Rivers, all tributaries of the Santiago River, in northwestern Ecuador. From the foregoing enumerations, together with the subsequent description of the placers of the Chocó district, it is evident that a platinum province extends from Panama almost to Chile, a distance of about 800 miles.

The placers of the Chocó province are the principal sources of platinum in South America. Modern exploration and mining of these deposits were begun in 1887, in the vicinity of Quibdó and have continued to the present time. The first dredge was built by a British company on the Condoto River in 1915, and the second a short time later on the Opogodó River. In 1918, however, a dredge was built by the American Gold and Platinum Co., and this was followed by five other dredges of which the last was built in 1938. Dredging in the interval 1918–66 was done mainly by this company and by its subsidiary, the Compañia Minera del Chocó Pacífico, but in 1963 these companies were merged with the International Mining Corp. The writer is greatly indebted to Mr. Patrick H. O'Neill, executive vice-president of the International Mining Corp. and chairman of the board of Pato Consolidated Gold Dredging, Ltd., for most of the up-to-date information on dredging operations in Colombia published in this paper.

Four dredges were operated by the International Mining Corp. in the Chocó district in 1963–64. One dredge operated near Chiqui Choqui on the San Juan River, at the western side of the Big Flat; another was located in the valley of the Opogodó River, in the central part of the Big Flat; and a third worked the stream placers near Tambito, at the upper end of the paystreak on the Tamaná River; and a fourth operated on another large flat within the basin of the Novita River and the Quebrada Carmen. All four of these dredges produce both gold and platinum metals, with platinum-gold ratios ranging from 3:1 to 1:22.

Mining by primitive methods also continues in the Chocó district, mainly in the valleys of San Juan and Atrato Rivers and their tributaries. According to Mr. O'Neill, between 20,000 and 25,000 natives are engaged in this work, and their total production is estimated to exceed by 30 percent that of the dredges. Most of this platinum is purchashed by speculative buyers, by whom it is smuggled into Panama. Hence the official output of platinum metals cited for Colombia is really less than half the true production.

Most of the natives recover the precious metals by hand panning, using a scooplike instrument to scrape the gravel into a wooden batea. Much of this mining is done along the margins of the valley floors and terraces, but the upstream ends of the river bars and the bottoms of the rivers (at low stages of water) are also worked. At some sites, the sand and gravel from the valley walls and terraces are washed by ditchwater in rocklined sluices, which are cleaned up daily or weekly. Bar and bottom mining are done entirely with bateas. The natives are not allowed to work closer than 100 meters to an operating dredge.

The production of platinum metals from Colombia, from 1778 to 1960 according to Quiring (1962, p. 93–94), was 3,357,500 troy ounces, to which should be added the production of 1961–65. Thus, the total recorded production from 1778–1965, inclusive, is approximately 3,446,500 ounces. The maximum production was in 1928, when the output was 61,985 ounces.

INTENDENCIA DEL CHOCÓ

GEOGRAPHY

The gold-platinum placers of the Chocó lie along the west flanks of the Cordillera Occidental, mainly in the valleys of the San Juan and Atrato Rivers. The San Juan River, which is the principal site of the platinum metals, flows southward, and then veers westward in southern Chocó to flow to the Pacific Ocean. The Atrato River flows northward through Colombia, and then veers westward into Panama, where it empties into the Caribbean Sea. The drainage patterns of the San Juan and Atrato Rivers within the piedmont province, together with the principal streams which lie between these two rivers and the Pacific Ocean, are shown in figure 7.

The Cordillera Occidental is a range of rugged mountains which rises to altitudes of 7,000 to 13,000 feet. Along its western flanks this range is drained by many streams with high gradients that have cut deep precipitous gorges. Among such streams are the eastern headwaters of the San Juan and Atrato Rivers. Between the Cordillera Occidental and the Pacific

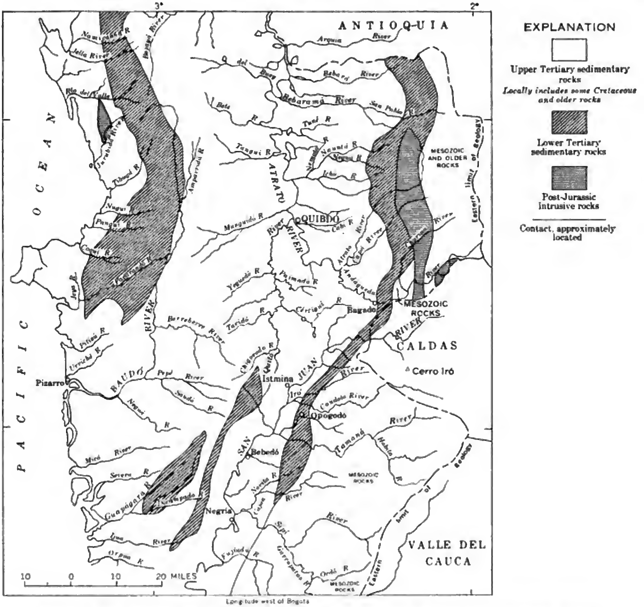

FIGURE 7.—Chocó platinum district, Colombia. (Modified from Colombia Servicio Geológico Nacional, 1946.)

Ocean is a low range of north-trending mountains, called the Serranía de Baudó, which is drained on the east by the Baudó River and on the west by smaller streams which flow directly to the Pacific. The Serranía de Baudó has altitudes ranging from 1,600 to 3,300 feet. A still lower range of hills, called the Serranía de Istmina, trends east-northeast and forms a divide between the drainages of the San Juan and Arato Rivers. This range rises eastward to a peak called Alto de Fernando in the Cordillera Occidental, with an altitude of 9,400 feet.

GENERAL GEOLOGY

The rocks exposed in the Intendencia del Chocó range in age from Precambrian to Tertiary, and strike generally northward, though in the upper valley of the San Juan River the regional strike veers to a direction ranging from N. 20° E. to N. 40° E. The stratigraphic sequence within the area whose drainage is shown in figure 7 comprises undifferentiated Mesozoic rocks, Cretaceous rocks, and lower and upper Tertiary rocks. Precambrian and post-Jurassic intrusives are also present.

The formations of genetic significance are two sedimentary Tertiary formations, described as upper and lower Tertiary in age, and a band of post-Jurassic intrusive rocks that lie east of the Tertiary rocks. The distribution of the lower Tertiary rocks and of the post-Jurassic intrusives, as they occur in the eastern part of the province of Chocó, are also shown in figure 7. Another and wider band of the lower Tertiary rocks occurs in the Serranía de Baudó, and between these two bands lies a broad stretch of upper Tertiary rocks, which attain a maximum width of 50 miles. West of the Serraní de Baudó, the upper Tertiary rocks reappear, and continue to the Pacific Ocean. Cretaceous and undifferentiated Mesozoic rocks form the country rock east of the Tertiary formations and the post-Jurassic intrusives. The distribution of the bedrock units suggests the presence of a broad shallow synclinal basin of Tertiary rocks, more tilted on its eastern than on its western flank. A sharp anticline is also indicated in the Serranía de Baudó. Quaternary alluvium occupies the valley floors of the San Juan and Atrato Rivers and their tributaries, mainly in the area occupied by the upper Tertiary rocks.

The lithologic character of the Tertiary rocks has not been described. The bedrock in streams where placer mining has been done includes both the upper and lower Tertiary formations, but consists dominantly of the upper Tertiary rocks, which from brief statements are inferred to consist mainly of gritty sandstone, conglomerate, and shale. Where such rocks are exposed in the beds of streams and along stream terraces, they are weathered to a red caliche, which is widely distributed. This red caliche is a gravelly clay, of which about half consists of well-rounded pebbles, cobbles, and boulders up to a foot in diameter. The lithology suggests that the upper Tertiary rocks are of terrestrial origin; the origin of the lower Tertiary rocks is not known. Nearly all the gravels of the upper Tertiary rocks are so greatly weathered that they may be broken by hand, though obviously they were not in this condition at the time of their deposition. The lithologic character of these upper Tertiary gravels is inferred to be virtually similar to the gravels of the present streams. Below the red caliche at many places, according to Singewald (1950, p. 173), is a gray caliche, which crops out, however, mainly in the area southwest of the Condoto and Cajón Rivers.

The post-Jurassic intrusive rocks have been mapped in a belt 2 to 7 miles wide, which extends from the headwaters of the Andágueda River, and they probably extend for some distance southward into the province of Caldas. These intrusives consist mainly of dioritic and gabbroic rocks, but include also some ultrabasic types. According to Duparc and Tikonowitch (1920, p. 478–483), the ultrabasic rocks occur mainly in isolated mountains that lie west of the main Cordillera Occidental; these include Cerro Torá, Cerro Iró, and Cerro Muñoa (Imperial Institute of Great Britain, 1936, p. 109). The approximate position of Cerro Iró is shown in figure 7. Duparc and Tikonowitch (1920, p. 479) describe these ultrabasic rocks as dunite, pyroxenite, and picrite and regard them as the primitive sources of the platinum metals. They further state that along the east side of Cerro Iró these rocks are in contact with a thin slice of more or less siliceous schists, to the west of which lie upper Tertiary shale, sandstone, and conglomerate.

The ultrabasic rocks were evidently bared to erosion in pre-late Tertiary time, so that a part of the precious metals originating in lodes to the east were deposited in the late Tertiary sediments, which thus constitute a secondary or proximate source of gold and platinum. The red caliche, which is the product of weathering of the upper Tertiary rocks, is therefore auriferous and platiniferous and owing to residual concentration probably contains more of these metals than the underlying unweathered horizons. At many localities, the Tertiary rocks and the caliche derived from them contain enough gold and platinum that they may be dredged, and thousands of natives are engaged in mining these deposits on a small scale. The gray caliche, where it occurs at the base of the fluviatile placers, is reported by Singewald (1950, p. 171) to be mainly barren of gold and platinum; and this is confirmed by Mr. O'Neill.

GOLD-PLATINUM PLACERS

All the deposits of the platinum metals so far found in Colombia are gold-platinum placers, wherein the ratio of gold to platinum varies from valley to valley. Moreover, except in a few tributaries of the San Juan River, the content of gold is greater than that of the platinum metals. Some of the characteristics of the platinum metals are stated in the descriptions of mining, but it should be added that a large part of the platinum is ferromagnetic. Iron pyrite is invariably one of the minerals in the concentrates recovered in the gold-platinum mining.

Gold lodes have been discovered in the headwaters of some of the streams of the Chocó district that head in the Cordillera Occidental, but no platinum lodes have been found. Certain isolated mountains along the west flanks of the Cordillera Occidental, however, are known to be the sites of intrusive rocks that include ultrabasic rocks which are considered to be the

primary sources of the platinum metals of the Chocó district.

The placer deposits include both stream and bench deposits. The stream placers were worked first to shallow depths by manual methods, and later to greater depths by machinery. The alluvium of the stream channels is underlain by red caliche which at many sites contains sufficient precious metals to be minable downward to the white caliche. Hence in working laterally outward from the stream gravels of the valley floor, no sharp demarcation exists between stream and bench deposits, except on high terraces or flats that are physiographically distinct. The high caliche flat, called the Big Flat, between the Condoto and Tamaná Rivers, exemplifies a terrace that may properly be called a bench deposit.

The gold-platinum placers of the Chocó district are mainly in the valleys of the San Juan River and the Atrato River and their tributaries, but those of the San Juan basin are the principal sources of the platinum metals, as most of the deposits of the Atrato basin are dominantly gold placers. The valley of the San Juan River has been mined from its headwaters to its mouth, and its eastern tributaries that have been or are being mined are the Iró, Condoto, Opogodó, Tamaná, Nóvita, Cajón, and Sipí Rivers. The town of Opogodó, in figure 7, lies on the north bank of the Opogodó River. The Mungará and the La Platina Rivers are headwater tributaries of the San Juan River. Four headwater tributaries of the Condoto River are the Tajuato, Apogo, Mestizo, and Tajuato Rivers. The Quebrada Carmen, hereafter mentioned, drains into the Nóvita River.

The principal streams in the Atrato basin that are mentioned as sources of the platinum metals are the headwaters of the Quito River (also called the San Pablo River) and two eastern tributaries of the Atrato River, called the Cértigui and the Andágueda Rivers. Placer mining has also been done on the Baudó River, but the deposits have not proved to be very important; and as gold is the principal precious metal, little platinum comes from this source.

The paystreak in the valley of the San Juan River extends from its headwaters downstream for 40 miles, by the course of the stream to the mouth of the Sipí River and has been mined throughout that distance. Parts of the valley, however, are still being mined and will probably continue to be worked for some years to come. The width of the paystreak has generally exceeded 200 feet, and in the Big Flat area, from the mouth of the Opogodó River to the Condoto River, the paystreak has a width of more than 3 miles. Farther downstream on the San Juan River is a paystreak from 300 to 1,000 feet wide, which will be worked in later years. Dredge 6, of the International Mining Corp., was working in 1963–64 in the San Juan Valley at the west side of the Big Flat, in the vicinity of Chiqui Choqui, about 1½ miles airline upstream from the mouth of the Opogodó River. This is a swampy area in which the depth to bedrock ranges from 40 to 60 feet, of which the upper 9 feet consist of soil. The gravel is of medium size and consists of about 5 percent quartz, with country rock from the east constituting the remainder. The bedrock is a gray to black caliche, which is soft and sticky, and contains no precious metals. Gold and platinum occur in the gravels from 10 to 60 feet above bedrock, but mainly at a depth of 20 to 30 feet below the surface. Considerable black sand is recovered with the precious metals. Screen analyses show that the sizes of the platinum grains range from 20 to 200 mesh, but 29 percent of them are of size 65 mesh, or about 0.0082 inch in maximum diameter. The platinum-gold ratio of the recovered metals is 1:1.7.

The Big Flat is an irregular area bounded by the Condoto, San Juan, and Tamaná Rivers, and the Opogodó River is the principal stream that dissects it. Dredge 3 was working in this flat in the Opogodó Valley in 1963–64, and mining has been extended to both sides of the river. The average depth to bedrock is 31 feet, of which soil forms the uppermost 8 feet. The bedrock is gray caliche, but at this site there is a gradual change from the red to the gray caliche. Most of the precious metals are found about 2 feet above bedrock, though at some sites they are found throughout the alluvium under the soil. The gravels are well rounded and medium to small in size and include about 10 percent quartz. The remainder consist of country rocks from the Cordillera Occidental, which are greatly decomposed and soft. The rocks differ in this respect from those at the site of dredge 6. Screen analyses of the platinum metals show that the grains range in size from 20 to 200 mesh, but a third of them are of size 65 mesh, or about 0.0082 inch in maximum diameter. The average platinum: gold ratio is about 1.6:1.

Dredge 2 was operating in 1963–64 in the Nóvita and Carmen valleys, in a large flat that is between the Tamaná and the Cajón Rivers. This is similar to the Big Flat that stretches from the Tamaná River to the Condoto River. The area is swampy and the depth to bedrock is 2.9 feet. The gravels are small and well-rounded and the consist of about 5 percent quartz, and all but the quartz are greatly decomposed. The bedrock is a soft sticky gray caliche. Most of the precious metals are concentrated on bedrock, but some of them extend upward into the gravel for 6 or 7 feet. Red garnet constitutes an important part of the concen-

trates recovered with the precious metals. Screen analyses show that the sizes of the platinum grains range from 20 to less than 200 mesh, with 1 percent smaller than 200 mesh. About half the grains range in size from 100 to 150 mesh, or with maximum diameters from 0.0058 to 0.0041 inch. The production of precious metals at this site is dominantly gold, with a platinum: gold ratio of 1:7.6. The fact that much of this platinum is silvery in color suggests the presence of osmiridium.

The Tamaná River has a paystreak that extends from its confluence with the San Juan River upstream for about 16 miles by the course of the stream, and has been mined throughout that distance. Dredge 4 was operating in 1963–64 in the riverbed of the Tamaná River and adjacent flats, near Tambito, which is at the upper end of the paystreak. The average depth to bedrock in the valley floor is 9 feet, but in the adjacent flats it is about 35 feet. This operation is within an area shown in figure 7 as lower Tertiary rocks, and the bedrock here is a hard black to gray shale, locally decomposed. The overlying gravels are large, with a third of them having diameters between 6 inches and 3 feet. Quartz constitutes about 10 percent of these gravels. The gold and platinum are concentrated in a zone from 2 to 3 feet above bedrock. Pebbles of magnetite (or ilmenite) up to three-fourths of an inch in diameter are a prominent part of the semiheavy minerals of the concentrates. The gold is coarse grained, and the platinum is only a little smaller. Nearly half the grains of platinum range in size from 48 to 64 mesh, or with a maximum diameter ranging from 0.012 to 0.0082 inch. This operation produces little platinum, as the platinum:gold ratio is 1:22.3.

Little information is available concerning the length, width, depth, and general character of the other paystreaks in the Chocó district. The paystreak on the Condoto River, however, is known to have extended from its confluence with the San Juan River upstream for about 15 miles. The depth to bedrock is from 9 to 35 feet; the deeper ground being doubtless along the lateral limits of the paystreak. The platinum from the Condoto placers consists of small flattened white grains, most of which have maximum diameters ranging from 0.0085 to 0.0065 inch, but the smallest grains are as small as 0.0025 inch. In the headwaters, where the coarsest grains occur, they are found attached to is 3:1, which is said to be the highest in the Chocó dis- (1956), the platinum:gold ratio on the Condo River is 3:1, which is said to be the highest in the Chocó district but this ratio is known also to be high in the valley of the Iró River. The concentrates recovered from the Condoto placers include ilmenite, a little magnetite, chrome spinel, chromite, garnet, pyrite, olivine, epidote, and a little zircon.

The stream gravels that form the workable placers in the Chocó district are a hetreogeneous assortment of well-rounded pebbles and cobbles, with some boulders similar, except for extreme weathering, to those present in the red caliche. They include numerous kinds of rocks eroded from the Cordillera Occidental and the rocks that bound this mountain range on the west. Shale, derived probably from the Cretaceous and early Tertiary rocks, is reported by Singewald (1950, p. 170) to constitute the principal gravels of the San Juan Valley, though fine-grained basic rocks, diorite, and graywacke were also noted. Other observers have reported the presence of some gravels consisting of schist, gneiss, diabasic greenstone, various intrusive rocks, lavas and basic and intermediate composition, conglomerate, and serpentine. Pebbles in quartz are not plentiful, but commonly constitute 5 to 10 percent of the gravels.

Tenors of some of the stream deposits mined in earlier years have been published, but in an area where many of the placers have been worked and reworked for scores of years, such tenors have more historical value than present significance. One estimate of this kind, made by a dredging company operating on the Condoto River in 1930, was an average tenor of $1.58 per cubic yard, based upon mean values of the platinum metals and local gold bullion respectively of $65 and $16.90 per troy ounce. But the average tenor of the placers that are now being dredged is between 10 and 15 cents per cubic yard, based upon values of the platinum metals and gold respectively of $70 and $35 per ounce.

NARIÑO PROVINCE

Dredging began on the Telembi River, in the province of Nariño, in 1938. The dredge, now owned by the International Mining Corp., is larger and stronger than any of those operating in the Chocó district, as it was designed to dig to a greater depth in more tightly consolidated gravel. This dredge, digging to a depth of 65 feet or less below water level, has worked from its initial site 9 miles downstream from Barbacoas up the valley of the Telembi River for 22 miles to the upper limit of dredging. It was moved in 1965 to a site below where it was constructed and has been modified to dig to a depth of 90 feet, to mine considerable reserves of such deeper ground. The width of this paystreak is not known to the writer, but it must be rather wide to have provided mining ground for 27 years. The gravels are mainly good sized cobbles of shale and slate, which are quite undecomposed and hard. The pre-

cious metals occur generally close to bedrock. The output of platinum metals is small, because platinum constitutes only 1½ percent by weight of the gold that is recovered.

CHEMICAL ANALYSES

The ratios of the six platinum metals to one another may be expected to vary considerably over an area so large as that heretofore described. These alloys include both ordinary platinum and osmiridium. Ten analyses of platinum metals are given in table 27. Three analyses of osmiridium are also available and are given in table 28.

Analyses, C, D, E and F appear to represent a single alloy consisting dominantly of platinum, with relatively small amounts of iridium and rhodium and still smaller amounts of palladium. Analyses A_2 and B_2 may include small amounts of intergrown or intermixed osmiridium. The analyses of table 28 indicate that the osmiridium represents a single alloy consisting dominantly of iridium and osmium, with less ruthenium and still less rhodium. These analyses indicate that the osmiridium alloy of Colombia appears to vary considerably in composition, ranging in tenors of iridium from 70 to 34 percent and in osmium from 17 to 55 percent. The mean analysis of the Colombian osmiridium correlates approximately with that from the Syssertsk area in the Urals, except that its mean tenor in rhodium is nearly five times as great as that of the Uralian product. A feature of this and of every other osmiridium known to the writer is the low content of iron and copper. This is due doubtless to the limited miscibility in solid solution of these base metals with osmium and ruthenium, which together constitute generally about 10 to 15 percent of the placer platinum.

TABLE 27.—*Analyses, in percent, of platinum metals from Colombia*

[N.D., no data]

	A_1	A_2	B_1	B_2	C	D	E	F	$Mean_1$	$Mean_2$
Pt	84.00	91.54	86.59	92.33	96.51	95.90	96.67	98.30	85.91	92.58
Ir	1.56	1.59	1.50	1.60	1.32	2.26			1.54	1.66
Os	.59	.64	1.06	1.12		.20			.57	.62
Os plus Ir	2.66	2.90			.48		2.74	1.09	2.11	2.28
Ru	N.D.	N.D.	N.D.	N.D.	N.D.	.02			.02	.02
Rh	2.12	2.30	3.55	3.79	.90	.88			1.90	2.06
Pd	.94	1.03	1.09	1.16	.79	.74	.59	.61	.72	.78
Cu	.51		.76						.53	
Fe	7.72		5.45						7.03	
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

A_1. Mean of five analyses (Kemp, 1902, p. 18, 19; Duparc and Tikonowitch, 1920, p. 280 and 189), including copper and iron.
A_2. Same as A_1, without copper and iron.
B_1. Codazzi (1920, p. 199-213), including copper and iron.
B_2. Same as B_1, without copper and iron.
C. Analysis by Johnson, Matthey and Co.
D. Big Flat. Analyst, E. R. Johnson. Published with permission of Johnson Matthey and Co.
E. San Juan River (Singewald, 1950, p. 174).
F. Condoto River (Singewald, 1950, p. 174).
$Mean_1$. Weighted mean analysis, including copper and iron.
$Mean_2$. Same as $Mean_1$, without copper and iron.

TABLE 28.—*Analyses, in percent, of osmiridium from Colombia*

[N. D., no data]

	G	H_1	H_2	I	$Mean_1$	$Mean_2$
Pt	0.10	N.D.	N.D.	Tr.	N.D.	0.10
Ir	70.40	57.76	57.86	33.89	57.76	53.36
Os	17.20	35.08	35.13	54.55	35.08	35.17
Ru	N.D.	6.37	6.38	.96	6.37	3.62
Rh	12.30	.63	.63	10.60	.63	7.75
Pd	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Cu		.06			.06	
Fe		.10		Tr.	.10	
Total	100.00	100.00	100.00	100.00	100.00	100.00

G. Kemp (1902, p. 21), without copper and iron.
H_1. Kemp (1902, p. 21), including copper and iron.
H_2. Same as H_1, without copper or iron.
I. Gmelin (1939, p. 182).
$Mean_1$. Mean analysis, including copper and iron.
$Mean_2$. Mean analysis, without copper and iron.

AUSTRALIA

Platinum metals have been found in four Australian states; and in earlier years a considerable production resulted, but since 1958 the output has amounted to only a few ounces per year. The formerly productive states, named in their order of relative importance, are Tasmania, New South Wales, Victoria, and Queensland. Osmiridium was discovered in Tasmania in 1876, and from 1899 until recent years, a production resulted which has amounted to about 31,400 ounces, with a maximum output in 1925 of 3,665 ounces. Platinum was found in New South Wales in 1851, and the total production from 1893 to the present time is estimated to have been about 20,000 troy ounces, with an output of 336 ounces in 1932. Victoria produced 311 ounces of platinum metals in 1911 and 1913, as the byproduct from a copper mine, but no further output is recorded. Platinum has also been found at other localities in Victoria. Small amounts of platinum metals have been found in several goldfields of Queensland, and the platinum metals occur also on the

oceanic beaches that extend southward into New South Wales. No production has been recorded.

TASMANIA

An excellent statement on the osmiridium deposits of Tasmania has been published by the Imperial Institute of Great Britain (1936, p. 78–84), and most of the material presented below was taken from that source. Osmiridium has been found in two principal areas in Tasmania, and from 1910 to 1922, when osmiridium began to be mined in the Witwatersrand, the Tasmanian osmiridium was the world's principal source of this alloy.

The two productive districts are known as the Heazelwood district, of northwestern Tasmania, and the Adamsfield district, of southwestern Tasmania. Osmiridium was first discovered in the Heazelwood district in 1876, in the valley of Wilson River and shortly thereafter in the valleys of Savage and Whyte Rivers. These three streams are tributaries of Pieman River, which discharges into the ocean about 70 miles south-southeast of the northwestern point of Tasmania. About 1899, osmiridium was traced up the valley of Savage River to its confluence with Nineteen Mile Creek, and up that stream to its bedrock source on Bald Hill. Other headwater tributaries of Savage and Whyte Rivers were likewise found to contain high-grade placers, and the Bald Hill area, within the Heazelwood district, soon became the principal source of osmiridium in Tasmania. A workable placer was also found in 1903 on Trindle Creek, in the Wilson River area. Ordinary platinum was also found in the Heazelwood district.

Bald Hill is part of an irregular body of serpentinite within an area of about 20 square miles, which lies north of a much larger mass of granitic rocks. South of these granitic rocks is a large dike of serpentinite with a length of about 11 miles and a maximum width of 1½ miles, which trends southeast. This is transected diagonally by Wilson River, which flows generally parallel to the Savage and Whyte Rivers. Ten or more smaller bodies of serpentinite lie east of the two main ones, and one lies south of the northern one. According to a geologic map of Tasmania (Tasmania Geological Survey, 1961), these bodies of serpentinite are of Cambrian age and intrude sedimentary rocks of Precambrian age. The total length of this Heazelwood belt, including the granitic rocks from Savage River to the vicinity of Dudas, is about 35 miles. The bedrock on Bald Hill consists of dunite, bronzitite, and peridotite, including serpentinite, and eventually a bedrock source of osmiridium was found along structural planes in the ultrabasic rocks, mainly within an area of about 500 acres. These bedrock sources, however, were too low grade for successful mining, except where they were so greatly weathered that they could be mined as detrital deposits.

Most of the osmiridium was recovered from placers, of which three sources were recognized. These were first, the weathered serpentinite atop Bald Mountain; second, the eluvial and stream placers; and third, certain buried placers that were covered by lava flows of Tertiary age. The eluvial and residual deposits were quickly exhausted, and one buried stream placer on Nineteen Mile Creek was worked by underground methods. The stream placers ranged in width from 30 to 150 feet, and in depth to a maximum of 15 feet. The osmiridium ranged in size from very fine grains up to nuggets that weighed several ounces, but little or no platinum was commonly found. The heavy minerals recovered with the osmiridium included gold, gold alloyed with platinum, chromite, picotite, magnetite, pyrrhotite, and pyrite.

The second platinum field of Tasmania is the Adamsfield district, which was discovered in 1925 and soon superseded in importance the deposits of the Heazelwood district. This district is in the northeastern part of Arthur County, southwestern Tasmania, about 55 miles west-northwest of Hobart. The general area is in the valleys of Adams and Eve Creeks, extending northward to Gordon River. The principal stream valleys from which osmiridium was recovered were those of Main and Lavelle Creeks and smaller tributaries of these two streams. The Adamsfield district yielded 12,500 ounces of osmiridium between 1925 and 1934, and progressively smaller amounts in later years.

The geology of the Adamsfield district is shown on a geologic map of Tasmania (Tasmania Geological Survey, 1961). The country rocks are of Precambrian, Cambrian, Silurian, and Devonian age, and a large dike of ultrabasic rock of Cambrian age is shown to invade the Precambrian sedimentary rocks. This dike trends north-south and has a length of 10 miles, and a width ranging from 1 to 1⅔ miles. It consists mainly of serpentinite, and has been proven to be the bedrock source of the osmiridium. In 1930, a lode deposit of osmiridium was located in the serpentinite and was worked successfully for several years. The ore body is a steeply dipping body of foliated serpentinite which lies between well-defined walls of dark-green massive serpentinite. The length of this ore body was about 700 feet, with a width ranging from 8 to 10 feet. The osmiridium was found to be distributed in veins that had a maximum thickness of 18 inches. The ore body was so softened by weathering that it could be disintegrated by a

giant and was therefore mined mainly as a detrital deposit, though it is recorded that equipment for crushing bedrock was installed in 1933.

Most of the production, however, came from stream placers that yielded mainly osmiridium, with a very small amount of native gold. The detrital minerals recovered with the osmiridium included a large volume of chromite, together with ilmenite, zircon, topaz, millerite, and pyrite, of which the two last mentioned were thought to be of secondary origin. Intergrowths of osmiridium and gold suggested a hydrothermal origin for both metals.

Platinum and palladium were also found in Tasmania, though not in economic quantity, in a copper-nickel lode mine near Zeehan, which is situated on Badger River, a short distance west of Dundas. According to The Imperial Institute of Great Britain (1936, p. 83), this deposit contained ore minerals with a tenor of 6 percent nickel, 3 percent copper, and a little gold, platinum, and palladium. The lode consisted of veins 1 to 4 feet thick, within bodies of gabbro, norite, and other basic intrusives.

Four analyses published by Quiring (1962, p. 120) of the platinum metals of Tasmania have been recomputed to total 100 percent, without the base metals, and are given in table 29. The Tasmanian osmiridium, represented by analyses A, C, and D, may properly be called iridosmine, as the tenors of osmium are invariably greater than those of iridium. Its nearest counterpart is the iridosmine of the Witwatersrand, but the total iridium plus osmium is considerably higher than that of the Witwatersrand, and the tenor in rhodium is only half as great. The small content of platinum shown in analyses A, C, and D indicate the presence only of a single alloy, rather than osmiridium intergrown with the common platinum alloy. Analysis B appears to represent a mixture of ordinary platinum and osmiridium, of which the former is a major component.

TABLE 29.—*Analyses, in percent, of osmiridium and platinum from the Heazelwood and Adamsfield districts, Tasmania*

	A	B	C	D
Platinum	0.37	66.63	1.18	1.95
Iridium		1.19	43.86	43.16
Iridium plus rhodium	33.92			
Osmium	57.28		47.92	46.54
Osmium plus iridium		28.22		
Ruthenium	8.22		6.74	8.09
Rhodium		2.01	.30	.26
Palladium	.21	1.95		
Total	100.00	100.00	100.00	100.00

A. Osmiridium from the Heazelwood district.
B. Platinum from the Heazelwood district.
C. Mean of 31 analyses of osmiridium from the Adamsfield district, originally published by Nye (1929).
D. Mean of an unspecified number of analyses from the Adamsfield district, made originally by Johnson, Matthey and Co., Ltd., of London.

The Tasmanian osmiridium has not merely a very high tenor in osmium and iridium, but also a very low tenor in platinum. It is well known that the solubility of one chemical element may be appreciably influenced by the presence of another element with a different solubility. Beamish stated (1966, p. 21) that the Tasmanian osmiridium (iridosmine) is more resistant to chlorinization that any other known osmiridium. Platinum is readily soluble in aqua regia, and it is possible that its paucity in the alloys represented by analyses A, B and D may explain the resistance of this osmiridium to chlorinization.

NEW SOUTH WALES

Platinum was first discovered in eastern New South Wales in 1851, in alluvial deposits near Orange, in Wellington County. The most important area, however, is the Fifield district of Cunningham and Kennedy Counties, in east-central New South Wales, about 215 miles N. 65° W. of Sydney and between the Lachlan River and the headwaters of Bogan River. This field was discovered in 1887, and beginning in 1893 soon became the largest producer of platinum metals in this state. For the first 30 years after 1893, the total output was about 20,000 ounces; thereafter, the deposits continued to be worked with steadily diminishing returns.

The bedrock formations of this area are mainly slate, sandstone, and limestone of Silurian age, overlain by sandstone and conglomerate of Devonian age. The platiniferous deposits consist of deeply buried gravels, probably of Pliocene age, which are covered by Pleistocene sediments of sand and clay, and locally by basaltic lava. These buried placers, called "leads," are less deeply buried and therefore more accessible toward the headwaters of the streams that formed them. The original discovery in this field was in a conglomerate on a low hill about 2 miles east of Fifield, but it is possible that this represents a remnant of an early Tertiary conglomerate that functioned as a proximate source of the precious metals for streams of late Tertiary age.

The Platina lead, discovered in 1893, has a linear workable extent of a mile from north to south, and widths from 60 to 150 feet. The ancient stream that produced this placer evidently flowed south, as the tenors decrease in that direction. The previous metals consist of platinum and gold in ratios ranging from 6:1 to 3:1, and they occur either on or in crevices in bedrock or in gravel a few inches above bedrock. Nuggets of platinum weighing as much as 1.35 ounces

have been recovered. A small amount of osmiridium is also present.

A similar deposit, called the North or Gillenbine lead, was discovered in 1917. This likewise extended north-south for about a mile, with widths ranging from 40 to 80 feet. The platiniferous gravel of this deposit lies 80 to 90 feet below the surface, and ranges in thickness from a few inches to 3 feet. The ancient streams at this site appears to have flowed northward, as the tenors are highest at the south end of the lead. The ratio of platinum to gold is about 8:1.

Three analyses of the platinum metals of the Fifield district are available; these analyses, recomputed to total 100 percent without the base elements, are presented in table 30. These analyses appear to represent the common alloy of platinum, with which was intergrown or intermixed some osmiridium, similar generally to the product from Platinum, Alaska. An exact comparison is not possible because ruthenium was not determined, and because in analysis B, palladium was not separated from rhodium.

TABLE 30.—*Analyses, in percent, of platinum metals, Fifield district, New South Wales*

[N.D., no data]

	A	B	C	D
Platinum	86.45	92.01	89.39	89.28
Iridium	1.48	.69	2.27	1.48
Osmium plus iridium	10.59	5.47	7.52	7.86
Rhodium	1.48	----	.53	1.01
Rhodium plus palladium	----	1.83	----	----
Palladium	Tr.	N.D.	.29	.37
Total	100.00	100.00	100.00	100.00

A. Platina lead, published by the Imperial Institute of Great Britain (1936, p. 76).
B. North lead, (Morrison, 1928, p. 121).
C. Mean analysis of platinum from New South Wales, by Johnson, Matthey and Co., Ltd., London.
D. Mean of analyses A, B, and C.

A less important area in New South Wales was the Richmond River district, which beginning about 100 miles south of Brisbane extended southward and westward for another 100 miles to include the valleys of Richmond and Clarence Rivers and continguous streams. The beach deposits at Ballina and Evans Head were also within this District. So far as can be learned, the Richmond River district never became very productive, but evidently osmiridium was one of the platinum alloys, as one analysis of osmiridium was published by O'Neill and Gunning (1934, p. 20). This analysis, recomputed to total 100 percent, is iridium 58.22, osmium 33.50, ruthenium 5.23, rhodium 3.05, platinum and palladium not determined. This osmiridium differs from that of the Witwatersrand and Tasmania in that the content of iridium is greater than that of osmium. It differs from the osmiridium of Japan in having a much lower content of ruthenium and rhodium, and it differs from the Colombian osmiridium in that the content of ruthenium is greater than that of rhodium. The closest counterpart is the osmiridium from Syssertsk, in the Urals. These differences show the high variations that may be expected in osmiridium.

Considerable has been written about the occurrence of platinum at Darling Hill, in the Broken Hill district, about 265 miles northeast of Adelaide. These are lode deposits, exposed at several localities, of which none has proved to have any commercial value. The country rock in their vicinity consists of high folded sandstone and shale, intruded prior to folding by pegmatite, amphibolite, and serpentinite. The platinum metals occur either in lenticular veins of serpentinite, or in narrow veins of hematite and limonite, at or near the contacts between serpentinite and country rock. Copper, nickel, and cobalt, as well as the platinum metals, gold, and silver are present in the ores. The genesis of these deposits has not been definitely established.

VICTORIA AND QUEENSLAND

Platinum metals were produced in southeastern Victoria in the period 1911–13, as a byproduct from the Walhalla copper mine, Gippsland district, about 80 miles east of Melbourne. The average tenor of platinum metals at this mine was 0.13 ounce per ton of copper and gold ore, and the total production was 311 ounces. The character of the platinum metals has not been published.

The bedrock formations in this area, according to a geologic map published by the Victoria Department of Mines (London, 1963), are Ordovician slates and sandstones, intruded by granitic rocks of unstated age and character, with nearby basaltic volcanics of Tertiary age. The copper ore is chalcopyrite, which occurs in dioritic rocks. Platinum metals were also found in pipes and dikes in the Walhalla-Wood's Point district. Osmiridium was found near Foster, about 40 miles southeast of Melbourne, and in the Waratah Range, of south Gippsland.

Alluvial platinum and gold were first found in southeastern Queensland in 1869 at Brickfield Gully, in the Gympie goldfield, on Mary River, about 90 miles N. 15° W. of Brisbane. Alluvial platinum has also been found in the Russell goldfield, near Innisfail, northeastern Queensland. Other localities are on Don River, about 40 miles south of Rockhampton, and along the oceanic beaches south of Brisbane, including Currumbin Beach, near the mouth of Tweed River. No production is recorded for Queensland.

NEW ZEALAND

Osmiridium was discovered in New Zealand in 1860. Platinum and platiniridium are also known to occur, and Morgan (1927, p. 76, 77, and 81–82) has listed 45 known localities. Five sites are mentioned by The Imperial Institute of Great Britain (1936, p. 86) and by O'Neill and Gunning (1934, p. 128) where the platinum metals occur in lode deposits; two in quartz veins, two in pyritic quartz veins, and one in massive pyrite. Three of these localities are on the North Island, and two on the South Island. None of the lode deposits has proved to be workable; and of the alluvial deposits, only those at the south end of the South Island have been mined.

The principal output of alluvial platinum came from the southern beaches of Southland, where an annual production of less than 20 ounces was made for several years and where the total production is estimated to have been between 100 and 200 troy ounces. The productive sites were along the north side of Foveaux Strait, from some point west of the mouth of the Waiau River east-southeast to the mouth of the Waikawa River, a distance of about 90 miles. These deposits occur both on the present and on the elevated beaches. The coarsest platinum came from the beach west of the mouth of the Waiau River. The principal precious metal is gold, and the highest recorded ratio of platinum to gold is 1:4, near Waiau River. Ratios as low as 1:100 are also known elsewhere on these beaches. In Nelson province, in the northwestern part of the South Island, platinum was also found in the gravels of Lee, Roding, and Maitai Rivers, but no production is recorded.

Analyses of the osmiridium and platiniridium of New Zealand have not been published. One analysis, however, of the platinum metals from Orepuki, South Island, was published by Farquharson (1913, p. 471). This analysis recomputed to total 100 percent, with and without iron and copper, is as follows:

	A_1	A_1
Platinum	74.36	78.44
Iridium	1.30	1.37
Osmium plus iridium	14.27	15.06
Rhodium	3.51	3.70
Palladium	1.35	1.43
Iron	5.06	--------
Copper	.15	--------
Total	100.00	100.00

This analysis suggests strongly that the analyzed product consisted of a major alloy of platinum, intergrown or mixed with a minor alloy of osmiridium. It resembles the high-iridium platinum metals found in the headwaters of Platinum Creek, of the Goodnews Bay district, Alaska.

PAPUA, TERRITORY OF NEW GUINEA, AND NETHERLANDS NEW GUINEA

Alluvial osmiridium occurs at numerous localities in Papua and has been mined in a small way at several sites, with a maximum annual production of about 355 ounces in 1921, and a total production said by Quiring (1962, p. 101) to have been about 1,350 ounces. Osmiridium, mixed with gold in unknown proportions, occurs on the beach at Milne Bay, at the extreme southeastern end of the island of New Guinea. Two other localities mentioned by O'Neill and Gunning (1934, p. 128) are the Yodda and the Gira Rivers, of which the latter is north of Owen Stanley Range, and about 240 miles northwest of Milne Bay. Another known locality is the Brown River, on the South side of the Owen Stanley Range and about 250 miles west-northwest of Milne Bay. Platinum also was discovered in 1933 in the Papuan jungle, about 120 miles west of Samarai.

The distribution of these localities shows that osmiridium and platinum occur over a distance of at least 250 miles in eastern Papua; and inasmuch as the platinum metals are known to be present in nearly every goldfield in Papua and in the other two divisions of New Guinea, it is concluded that these metals have a very wide distribution. According to E. R. Stanley (1932, p. 56), there are many areas and belts of peridotite and serpentinite in the mountain range that crosses New Guinea; and he surmised that the platinum metals might be found in the valleys of many streams that drain this range. This is further indicated by the discovery of platinum in the headwaters of Ramu River, north of Bismarck Range, in the Territory of New Guinea.

BORNEO AND SUMATRA

Platinum was discovered in Borneo in 1831, and from that date to 1922, it is estimated by Quiring (1962, p. 93) that the total production has been about 53,700 troy ounces, with a maximum of about 2,890 troy ounces for the period 1866–90, or an average annual production for these 5 years of about 580 ounces per year. Borneo has not been productive for many years.

Platinum and osmiridium were found both in the gold and in the diamond placers of southeastern Kalimantan, Borneo, and also in West Borneo between South Borneo and Sarawak. The richest deposits were apparently in the gold-platinum placers of Goenoeng-Lawack, near the boundary between the Tanah-Laut

and Martapura, east of Bandjarmasin. Stauffer (1945) corroborates the recovery of small amounts of platinum, together with diamonds, from the placers of Martapura. The streams of this area, according to the Imperial Institute, drain the Bobaris Mountains. Kemp (1902, p. 82–83) also mentions in the same region the Banjermassing River, which drains the Ratoos Mountains. The bedrock in these mountains evidently includes dikes and larger bodies of serpentinite, gabbro, and diorite; and the platinum and osmiridium are doubtless derived from the basic and ultrabasic rocks. The ratio of gold to platinum is stated to range from 9:1 to 10:1, and in the diamond placers, the ratio of diamond to platinum is about 1:1. Concentrates recovered from the gravels are stated by different writers to include chromite, cinnabar, topaz, zircon, and diamond.

Four analyses of platinum (table 31) and four analyses of osmiridium (table 32) are available for the Goenoeng-Lawack region, Borneo.

TABLE 31.—*Analyses, in percent, of platinum metals, Goenoeng-Lawack region, Borneo*

[Analyses recomputed to 100 percent. N.D., no data]

	A	B	C	D	Mean$_1$	Mean$_2$
Platinum	73.98	74.64	84.15	74.89	76.57	84.13
Iridium	6.46	8.22	.67	3.18	4.61	5.06
Osmium	1.21	.50	.31	N.D.	.67	.73
Osmium plus iridium	9.30	8.75	3.87	9.23	7.76	8.52
Osmium plus ruthenium				1.30		
Rhodium	.53	N.D.	N.D.	.64	.54	.60
Rhodium plus palladium		1.34				
Palladium	1.52			.24	.86	.96
Iron	6.11	6.10	10.87	10.08	8.51	
Copper	.89	.45	.13	.44	.47	
Total	100.00	100.00	100.00	100.00	100.00	100.00

A, B. Nuggets (Bleekrode, 1858, p. 666; republished by Kemp, 1902, p. 82).
C. Nugget (Böcking, 1855, p. 243; republished by Kemp, 1902, p. 82).
D. Quiring (1962, p. 158).
Mean$_1$. Mean of analyses A–D, including iron and copper.
Mean$_2$. Same as mean$_1$, without iron and copper.

TABLE 32.—*Analyses, in percent, of osmiridium, Goenoeng-Lawack region, Borneo*

[Analyses recomputed to 100 percent]

	E	F	G	H	Mean$_1$	Mean$_2$
Platinum	3.13	1.93	0.10	0.20	1.34	1.35
Iridium	62.02	58.15	53.58	17.25	47.78	47.95
Osmium	30.56	38.30	35.31	68.89	43.24	43.40
Ruthenium	Tr.	.25	6.29	9.03	3.89	3.90
Rhodium	3.33	1.01	4.67	4.57	3.39	3.40
Iron	.45	.28	.02	.03	.20	
Copper	.51	.08	.03	.03	.16	
Total	100.00	100.00	100.00	100.00	100.00	100.00

E–H. Quiring (1962, p. 158).
Mean$_1$. Mean of analyses E–H, including iron and copper.
Mean$_2$. Same as mean$_1$, without iron and copper.

Analyses A, B, C, and D (table 31), because they were made of nuggets, should yield a good value for the dross, of which the mean value is seen to be 8.98 percent. The fact that analyses A, B and D have high tenors for iridium plus osmium suggests that they are intergrowths of a major alloy of platinum with a minor alloy of osmiridium, but analysis C appears to represent a single alloy with a still smaller content of osmiridium. Analyses E, F, G, and H (table 32) represent alloys of osmiridium alone, but show variations of such a magnitude that they do not correlate closely with any others shown in this report.

Laurite, the sulfide of ruthenium and osmium, was first identified in Borneo by Wöhler (1866). The composition which he gave for this mineral, stated in percentages, was ruthenium 65.18, osmium 3.03, and sulphur 31.79. Owing, however, to the small size of the sample available for analysis, Wöhler was uncertain of the correct formula that should be assigned.

Platinum occurs in Sumatra, but no production has been recorded. Sumatra is best known for a peculiar lode, which occurs in the province of Sumatera Utara, about 35 miles inland from Sibolga, near the main highway. This lode was described originally by Hundeshagen (1904, p. 550–552) and has been republished by other writers, notably O'Neill and Gunning (1934, p. 123–124). The deposit contains ore of grossularite and wollastonite, with some bornite and secondary malachite, which have resulted from the contact metamorphism of a layer or lens of limestone by an intrusion of granodiorite. Assays revealed a tenor in platinum of about 0.18 ounce per ton of ore, all of which appears to have been contained in the wollastonite. Stauffer (1945, p. 332) also states that platinum was recovered from metamorphosed limestone as a byproduct of the Bengkalis gold mines.

JAPAN

Platinum metals were first recognized in Japan about 1890 in the gravels of the Yubari and the Sorachi Rivers, tributaries of the Ishikara River, within the provinces of Iburi and Ishikari, in the western part of Hokkaido Island. Probably the most productive area was in the valley of the Uryu River, the principal headwater tributary of the Ishikara River. Other placers were found on the Obirashibe River, west of the Uryu River, farther north of the Teshio, Tombetsu, and other streams, and along the western beaches of Hokkaido Island, between Kawashri and Embetsu. Placers were also found south of the Ishikara River, on the Mu, Hidaka, and other streams, and on certain beaches in the province of Iburi. Thus, the platinum deposits were confined largely to the western slope of Hokkaido. Other alluvial deposits, most of which were nonproductive, were found northward from Hitachi, on Honshu Island, on Sado Island off the west coast of Honshu Island, on Shikoku Island, and at other numerous sites, including the northeast coast of Hokkaido Island. Practically all the past production,

however, has come from Hokkaido Island, and most tables in the literature concur in this generalization.

The data on past production are contradictory, and the evidence indicates that placer production has at times been compiled with production from refineries and even with imports of platinum metals. It is estimated by Quiring (1962, p. 101) that the total output from 1909 to 1933 was about 8,000 troy ounces, with a maximum production of about 1,770 ounces in 1918. Pollard (1951, p. 8–9) has published a table based upon certain assumptions, which may or may not be valid. Taking, however, the minimum values given in his table, it appears that the total output from 1892 to 1950, when production ended, was about 10,000 troy ounces and that the maximum production was in 1944 and 1945, when 687 and 647 troy ounces respectively were recovered. Most of the deposits were placers of osmiridium and gold, and the more important ones showed ratios of osmiridium to gold ranging from 3:1 to 9:1, but at one locality near Tomarinai, the osmiridium was almost free of native gold. At the less important sites, the ratios of platinum to gold were much lower.

The principal areas of serpentinite in Hokkaido are shown by Pollard (1951, p. 26) to be coextensive with the osmiridium placers. Thus large bodies of serpentinite crop out in the upper valley of the Uryu River, and between the valleys of the Teshio and the Tombetsu Rivers in northern Hokkaido. Scattered, but important, bodies of serpentinite are also present in the valleys of the Mu and the Hidaka Rivers, northeast of Mukawa. The platinum metals have not been found in bedrock, but without doubt these metals originated in the serpentinite. Four types of alluvial deposits are known, of which the principal and most important ones are gravels in the present valley floors of streams that drain areas of serpentinite. A second type comprises terrace gravels in the same streams, which have altitudes up to 60 feet above the valley floor, and in some valleys extend laterally from the master stream as much as half a mile. These might amplify considerably the reserves of osmiridium, but have been little prospected. A third type of deposit, which may constitute a proximate source of osmiridium, are certain Tertiary conglomerates mentioned by Pollard (1951, p. 13). The fourth type constitute the beach placers.

The platinum metals are mainly osmiridium, which according to Pollard (1951, p. 3) constitute more than 80 percent of these metals, the remainder being ordinary platinum. The grains of osmiridium in the stream placers range in size from 30 to 100 mesh, or approximately from diameters of 0.02 to 0.006 inch; those on the beaches range from 100 to 200 mesh, with diameters approximately of 0.006 to 0.003 inch. The largest nugget known to have been found on Hokkaido Island weighed 0.315 troy ounce. The accessory minerals of the concentrates are mainly chromite and magnetite, though cinnabar has been recorded from some of the placers.

Four chemical analyses of the osmiridium are available and their values, recomputed to total 100 percent, are given in table 33. The tenor in iridium is higher

TABLE 33.—*Analyses, in percent, of osmiridium, Hokkaido Island, Japan*

[N.D., no data]

	A	B	C	D	E
Platinum	0.15	N.D.	Tr.	Tr.	0.15
Iridium	50.37	47.04	43.10	50.98	47.82
Osmium	37.73	35.78	38.48	33.08	36.22
Ruthenium	7.78	12.02	12.52	11.52	10.95
Rhodium	3.97	5.16	5.90	4.42	4.86
Total	100.00	100.00	100.00	100.00	100.00

A. O'Neill and Gunning (1934), p. 124.
B. Gmelin (1939, p. 145). Mean composition of fine and coarse grains.
C and D. Pollard (1951, p. 23).
E. Mean of these four analyses.

than in the osmiridium of the Witwatersrand, and platinum and palladium are virtually absent. The osmiridium from Syssertsk, though somewhat similar in that iridium is more plentiful than osmium, differs, in containing some platinum and in having much lower contents of ruthenium and rhodium, and much the same comparison may be made with the osmiridium from Borneo. The osmiridium from Colombia contains twice as much rhodium as ruthenium. Owing to inferior analyses of the Tasmanian product, an accurate comparison cannot be made, but in general the Tasmanian osmiridium contains platinum and has a very low content of rhodium. A worldwide appraisal of all the known osmiridium, as described in this report, indicates that this alloy does not approach a constant composition, but shows instead marked differences in the contents of iridium, osmium, ruthenium, and rhodium. The common characteristic is that the content of platinum is low or lacking and that palladium is almost entirely absent.

OTHER COUNTRIES

Platinum metals are known to occur in certain of the nickel-copper deposits of Norway, but most of these were exhausted years ago. These metals appear to be contained in sulfides, especially in chalcopyrite, which occurs in or close to bodies of magmatic segregations of norite and gabbro. The ratio of platinum to palladium was about 1:2, and their combined tenor was reported to have been about 50 cents per ton of ore. According to Quiring (1962, p. 97), the total

Norwegian output for the period 1927–38 was about 1,320 troy ounces, with maxima in 1930 and 1934 of about 190 ounces.

Refineries in Germany, Japan, and Italy, engaged in the refining of gold and copper, also contribute considerable amounts of platinum metals. In Germany, platinum and palladium are produced in processing the Kupferschiefer of the Mansfeld district, and these metals are also recovered in the refining of gold and copper. The extent of this industry in Germany has been reported by Rhodes, Jahn, and Dowson (1945, 53 p.).

The amounts of platinum and palladium recovered from the Mansfeld Kupferschiefer in 1929, according to Quiring (1962, p. 148), were respectively 0.0000167 and 0.0000138 ounce per ton. Quiring also cites 16 minerals that have been found in different parts of Germany, which had tenors in the platinum metals ranging from 0.0032 to 0.157 ounce per ton, but these were not minable ore deposits. The highest tenor was in a psilomelane from the Harz Mountains.

A locality in Guyana is of interest because it was the site of the discovery in 1923 of potarite, a rare compound of palladium and mercury. This was found near the Kaieteur Falls of Potaro River but was later found over an extensive area in the Potaro district. According to Spencer (1928), potarite is a definite compound of palladium and mercury in equal atomic proportions, but in this paper it is classified as a palladium amalgam. Platinum has also been reported in the Lawa River, in Surinam.

Platinum was first discovered in 1904 in the gold placers of Madagascar, where it was recovered at several localities; but the annual production never exceeded 10 ounces. One particular locality, given by The Imperial Institute of Great Britain (1936, p. 98), is of interest because an analysis was made of the platinum metals. This site is about 40 miles northwest of Vangaindrano in the valley of the Isonjo River, a tributary of the Manambia River, a left limit tributary of the Mananara River. A chemical analysis of this alluvial platinum, recomputed to total 100 percent, with and without iron and copper, is as follows:

Analysis, in percent, of platinum metals, southeastern Madagascar (Malagasy Republic)

Platinum	87.10	95.19
Iridium	1.97	2.14
Osmium plus iridium	1.38	1.51
Rhodium	.74	.81
Palladium	.32	.35
Iron	7.43	-------
Copper	1.06	-------
Total	100.00	100.00

This analysis indicated the absence of osmiridium.

Platinum and osmiridium have also been found in the auriferous gravels of the rivers draining both slopes of the Patkoi Range between northern Burma and Assam. A small amount of platinum was definitely recovered, according to The Imperial Institute of Great Britain (1936, p. 73), from the headwaters of the Irrawaddy River, north of Myitkyina. Platinum has also been described from numerous other localities in Burma, but no production has resulted.

UNITED STATES

Platinum metals have been found at many localities in the United States, but significant amounts of these metals have been produced at only three places. The principal source of platinum metals has been the placers of the Goodnews Bay district, western Alaska; another Alaskan source was a copper lode on Kasaan Peninsula, southeastern Alaska, which was worked for a number of years; and the third source has been the dredges of California, which for many years produced small amounts of platinum metals as a byproduct of gold placer mining. Smaller amounts of platinum have similarly been recovered from the gold placers of Oregon and Washington, and minor amounts from the placers of Montana, Idaho, and other Western States. A very small output has also come from some of the gold placers of Alaska.

Lodes that contained the platinum metals have been prospected and worked on a small scale in Wyoming, Nevada, Montana, and Colorado. In addition to these cited occurrences, traces or small amounts of the platinum metals have been found in 13 other States, as shown in table 10. Some of the minor deposits that have scientific interest will be briefly discussed, though none of them has economic significance.

ALASKA

LODES

SALT CHUCK MINE

The Salt Creek mine, formerly called the Goodro mine, is at the northwestern extremity of Kasaan Peninsula, about 36 miles N. 60° W. of Ketchikan. This property was described in considerable detail by Wright (1915, p. 99) at the time of his visit in 1908, when it was recognized as a small producing copper mine. The ore deposit differs from most others in that vicinity in that bornite is the principal copper-bearing mineral, though the ore also includes chalcopyrite, with small amounts of chalcocite, native copper, and gold. These ore minerals occur as small masses and disseminations in pyroxenite, gabbro, and gabbro pegmatite, all of which are differentiated products of the regional granitic rocks. The principal rock-

forming mineral is augite, in addition to which are biotite, iron ores, plagioclase, apatite, and sphene. The pyroxene and plagioclase are locally much altered to epidote, and to chloritic and sericitic minerals.

The Salt Chuck ore, until 1917, had been rated as a small low-grade copper deposit, with a mean tenor of 1.4 percent copper and a small byproduct of gold and silver. In 1917, however, the owners of this property discovered that their ore also contained platinum metals, which thenceforth became the principal product of mining. The property was visited in 1917 by the writer, (Mertie, 1920, p. 17–20) shortly after this discovery was made, and he was able to describe the deposit in the light of this new information. The country rock is much fractured, but most of the copper ores occur as disseminated deposits in irregular ore shoots. Some of the Chalcopyrite, however, occurs along planes of fracture. The ore body is considered to be an epigenetic deposit.

The platinum metals occur both in the copper minerals and disseminated in the pyroxene and gabbro. The form in which these metals exist is not known, but probably they are not native alloys. This is generally true in deposits of this type, as seen in Sudbury, Canada. At the time of the writer's visit, the smelter had informed the owners of the property that platinum and palladium had a ratio of 1:50, and this was reported by the writer in his description of the property. Subsequent developments, however, contradict this statement. Thus, Brooks (1922, p. 23) gives the production of platinum from Alaska in the years 1917–20, practically all of which came from the Salt Chuck mine, and the average value per troy ounce of this output was $115.63. Smith (1929, p. 39) quotes the Department of Commerce to the effect that 3,566 troy ounces was produced at this property in 1926, with an average value of $76.82. Obviously these outputs could not represent a product that was 98 percent palladium, as this metal has for years been the cheapest of the platinum metals. The designation of the Salt Chuck mine as a palladium-copper mine is therefore incorrect, as it should be called a platinum-copper mine. Owing mainly to litigation, this property was closed at the end of 1926 and has not subsequently been reopened.

PLACERS

GOODNEWS BAY DISTRICT

Mining and production

Platinum was discovered in 1926 at the mouth of Fox Gulch, a headwater tributary of Platinum Creek, by an Eskimo named Walter Smith. The sample, after passing through the hands of two other men, was sent to the U.S. Bureau of Mines, at Fairbanks, Alaska, where it was analyzed and determined to be platinum. In 1928, platinum was discovered in the gravels of Clara Creek, and in the same year it was discovered on Squirrel Creek. Details regarding these discoveries have been published by Irving Reed in Alaska, Supervisory Mining Engineer, (1933, p. 103–126). Eventually the Goodnews Bay Mining Co. acquired title to most of the productive ground on Salmon River and its tributaries and since 1940 has been the sole operating company.

A sketch map of the placer mining claims was published by the writer (Mertie, 1940b); but resurveys, the consolidation of some claims, and new locations have rendered this map obsolete. A new claim map is therefore included in this report (fig. 8). Unlike the original map, the names of the bench claims are not given, except for those to which reference is made in the text.

The Clara Creek Mining Co., using a dragline excavator, began mining on Clara Creek in 1936, and in the next 4 years worked out Clara and Dowry Creeks. This company also did some mining on Dry Gulch, a northern tributary of Platinum Creek. The Goodnews Bay Mining Co., likewise operating with a dragline excavator, began mining on Platinum Creek in 1934, and continued through 1941 until the placers of Platinum Creek, Fox Gulch, and Squirrel Creek were worked out. Thereafter this company, beginning on the association claim opposite 9 above Discovery, worked the bench placers of Salmon River for 11 years, ending this operation on the Bobby bench, opposite claim 3 above Discovery. From this point downstream, all mining was done by dredging.

A dredge was built by the Goodnews Bay Mining Co. in 1937 at the upper end of claim 1 below Discovery, Salmon River. This dredge worked upstream from its original site to claim 1 above Discovery, and turned working downstream to claim 7 below Discovery, where in 1942 it turned again and worked upstream to claim 5 above Discovery. Turning again in 1947, it worked downstream to claim 2 above Discovery, where in 1949 it moved eastward onto what is hereafter designated as the bench paystreak. Starting on the Ethel bench claim, the dredge worked sinuously but generally southward across the Palladium, Osmium, Ruthenium, Rhodium, Platinum and Iridium bench claims to Discovery claim, of Snow Gulch; and thence, from 1955 to 1963, it worked southward to the Olson Bench claim. At this point the alluvial cover became too thick for economical dredging, even though 40 feet of the overburden was being removed by a dragline excavator; and therefore the dredge moved westward onto the paystreak of the valley floor of Salmon River. Starting on claim 10 below Discovery, the

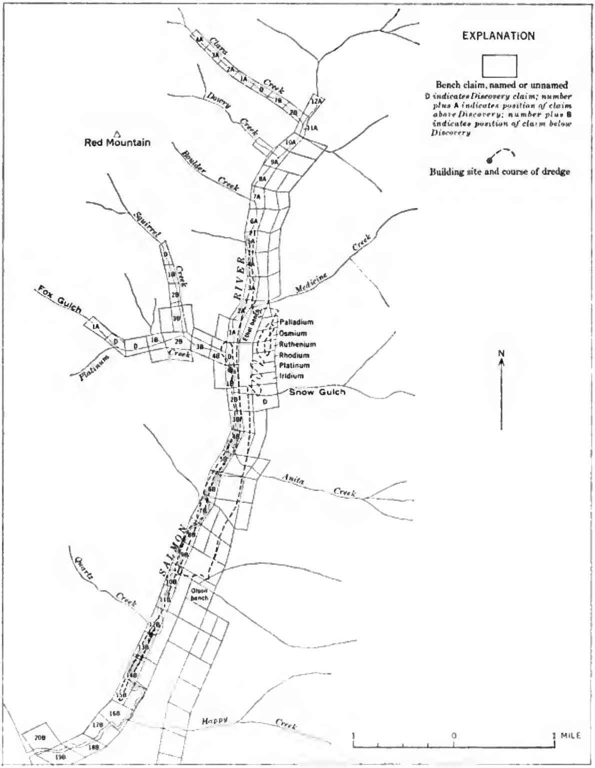

FIGURE 8.—Location of principal mining claims on the Salmon River and its tributaries.

dredge worked upstream to claim 8 below Discovery, where in 1964 it turned and began working downstream. In 1966, at the lower end of claim 15 below Discovery, the dredge again turned, and will continue to work upstream to claim 5 below Discovery. Thence it will move eastward onto the bench paystreak, and begin to rework tailings. Unworked ground also remains to be mined from claim 6 above Discovery to claim 11 above Discovery. The site where the dredge was built, and the course it has followed from 1937 to 1967 are shown in figure 8.

The bench paystreak continues south-southwestward for about 2 miles from the Olson bench claim, then veers southeastward toward Chagvan Bay. Much of this ground has been prospected by drilling, but the limits and tenor of the paystreak have not yet been precisely determined. It is known, however, that the depth of bedrock continues to increase, approaching 250 feet near Chagvan Bay. New methods ond equipment will be needed to mine this lower stretch of the bench paystreak. If the tenor will stand the cost, a belt conveyor may be used to dispose of a large part of the overburden.

The total production of platinum metals from Salmon River and its tributaries in the period 1934–66, including the output from Clara Creek, is estimated to have been well more than half a million troy ounces, with a maximum output in 1938 of 31,960 ounces.

Earlier and recent surveys

The general and economic geology of the Goodnews platinum district, a description of the placers, and a discussion of the character and composition of the platinum metals was published by the writer Mertie, (1940) in U.S. Geological Survey Bulletin 918, based upon a survey made in 1937. At the same time, a topographic map on a scale of 1:62,500 with 50-foot contours, was prepared by Gerald Fitz Gerald. In 1950, a new topographic map of a part of this district was made by the U.S. Coast and Geodetic Survey, on a scale of 1:63,360. This map, however, did not extend far enough north to show the settlement of Platinum, nor did it extend as far to the east as was needed. Accordingly, the original map by Fitz Gerald was enlarged to the scale of 1:63,360, and joined to the Coast Survey map, to produce the new map which is utilized in this report for charting the geology.

Much has been learned since 1937 regarding the distribution and character of these platinum metals by mining and exploratory drilling. To acquire the latest relevant information, the writer revisited this area in 1966 and again in 1968; and the owners of the Goodnews Bay Mining Co. cooperated by making available all their mining records since 1934. A great deal of other information was obtained from the owners regarding the placers that bears directly upon the Pleistocene history of this district. Collateral data have also been obtained from the work of David Hopkins and other geologists of the U.S. Geological Survey, who have been studying submarine gold placers, offshore from Nome. Arthur F. Daily, a consulting mining engineer, has also supplied much pertinent geologic information.

General geology

The bedrock formations of the area, exclusive of intrusive rocks, comprise highly folded sedimentary rocks with some tuffaceous beds, overlain by lavas and tuffs, all of which are believed to be of late Paleozoic age. In late Mesozoic or Tertiary time these rocks were invaded by ultrabasic intrusives, and at a somewhat later date by granitic rocks. The ultrabasic rocks are of two general types, of which one is composed largely of olivine and the other of pyroxene with variable, but distinctly smaller, amounts of olivine. The olivine rock, or dunite, is the principal bedrock of Red Mountain, and about a quarter of it is altered to serpentinite. Olivine-bearing pyroxenite forms the ridge southwest of Susie Mountain. The granitic rocks occupy the long ridge southeast of the headwaters of Smalls River. The dunite and serpentinite are the bedrock sources of the platinum metals that are recovered from the placers of Salmon River and its tributaries. The granitic rocks are believed to be the sources of a small amount of gold that is also contained in the placers. The platinum metals have not been found in place, but much has been learned regarding their occurrence and character in bedrock, from the disposition and patterns of the areal drainage system, and from analyses of the platinum metals at many recorded sites in the valleys.

The Tertiary history of this region, from the time of the invasion by granitic rocks to the end of the Pliocene epoch, is obscure, but it seems probably that during most of this period the area was above sea level. Much more information, however, is available regarding the Quaternary period, though the regional geologic history during the Pleistocene epoch has proven to be a complex problem. In 1937, when the first geological survey of this area was made, all glaciation in western Alaska was referred to the Wisconsin Glaciation of the Pleistocene Epoch, and in the Goodnews Bay district, no consideration was given to

the other glacial and interglacial stages that might have existed. This situation was changed in 1940, when a pre-Wisconsin Glaciation was recognized by the writer in the tin country of northwestern Seward Peninsula, and later that year was corroborated at Nome. This information was published in a paper by MacNeill, Mertie, and Pilsbry (1943, p. 69–96). Seward Peninsula and the Goodnews Bay district differ from the region south of the Alaskan Range in that the Wisconsin ice of southern Alaska extended to and beyond the Pacific strand line and regardless of whether an older glaciation had occurred, all traces of it have been obliterated, though its presence was recognized by Capps (1931, p. 1–8) north of the Alaskan Range. In western Alaska, however, the older glaciation was much more extensive than the Wisconsin ice, so that the evidence for its existence has been preserved.

Glaciations of Nebraskan, Illinoian, and Wisconsin age [2] have now been recognized on Seward Peninsula, though evidence for a glaciation of Kansan time is still lacking. High mountains exist in the region east and northeast of Goodnews Bay, as in the central part of Seward Peninsula, and it seems probable that a similar Pleistocene history prevails in this district. In fact, at least three glacial stages seem necessary in order to explain the geochronology of the placer deposits. The Wisconsin ice, as at Nome, is believed not to have extended to the present strand line, but in any event, it appears to have had little or no effect upon the formation of the placers in the valley of the Salmon River. One of the earlier ice streams, however, possibly of Nebraskan age, was so extensive and thick that it overrode completely, or nearly so, the ridges on both sides of the Salmon River. But the course of that stream was athwart the flow of the ice, and this explains why the placers of that valley were not eroded and obliterated. The same, or more probably a later glacier of Illinoian(?) age, severed and destroyed a placer deposit in the lower valley of Salmon River, where it was not protected by bounding hills. Evidence for this overriding ice sheet consists of the presence of a small amount of free gold, not merely in the platinum placers of the Salmon River, but more particularly in the placers of Platinum Creek and of Fox Gulch, its headqater tributary. This gold, not derived from the ultrabasic rocks of Red Mountain, is believed to have been concentrated from glacial deposits derived from the overriding ice, which possibly was of Nebraskan(?) age. Another significant occurrence is the presence of granitic erratics at the northern end of Red Mountain, at a maximum altitude of 825 feet above sea level. These were probably deposited by Illinoian(?) ice, and show that, although this ice did not flow down the valley of the Salmon River, it must have deposited morainal and glaciofluvial materials at the head of that stream, which were moved downstream in that valley and were subsequently transported seaward.

Two paystreaks exist in the valley of the Salmon River. One of the significant features of both these alluvial deposits is that the underlying bedrock, at their lower ends, is far below present sea level. If this condition is related solely to eustatic changes in sea level, it follows that both these paystreaks were formed during glacial stages, when sea level was much lower than it is at the present time and glaciation was nonexistent in the main valley of the Salmon River.

This brief history of glaciation during the Pleistocene Epoch yields a geochronologic record that is patently incomplete; but the preceding statements of fact, with tentative interpretations, when coupled with the following descriptions of the two paystreaks in the valley of the Salmon River, will constitute an initial hypothesis which should lead eventually to a more complete understanding of the Quaternary history.

Deposits

Practically all the platinum metals so far found in this district occur in placers within the valley of the Salmon River and its western tributaries that head in the dunite of Red Mountain. Susie Creek, a small south-flowing tributary of Medicine Creek, that heads in the pyroxenitic rocks west of Susie Mountain, drains an area of ultrabasic rocks but contains no workable paystreak. The tributaries of the Salmon River that head in the Paleozoic sedimentary rocks and the overlying volcanic rocks are quite devoid of platinum. These include Quartz Creek, on the west side of the Salmon Valley, and Medicine Creek, Snow Gulch, Anita Creek, and Happy Creek on the east side.

This localization of the platinum metals in Red Mountain led naturally to a search for deposits of these metals along the west side of this mountain. No large streams are present, but a large volume of eluvial and alluvial deposits blanket its western slopes, and extends to Kuskokwim Bay. A large amount of drilling and manual prospecting has been done along this foreland, notably during the summer of 1937, when several drills were working; but virtually no platinum was found. Beach placers along the shore of Kuskokwim Bay are likewise absent, because the strand lines at the times when the paystreaks were being formed were far west of the present strand line. In

[2] The names commonly applied to the glacial and interglacial stages of the Pleistocene Epoch are used in this report only to indicate chronologic sequence, and are not intended to imply close correlation with these stages in the northeastern United States and Canada.

later years, however, a little platinum was found and recovered from a small amphitheatrical opening in the southwest wall of Red Mountain, a short distance north of the low pass at the head of Platinum Creek.

Alluvial deposits of the platinum metals might also be expected to exist along the north side of Red Mountain, particularly because the dunite crops out along the north side of the Smalls River. But this stream has been deeply eroded by an Illinoian(?) glacier, which also scoured the northwest side of Red Mountain. However, a drill hole was sunk 192 feet to bedrock by the Goodnews Bay Mining Co. along the north side of the automobile road, about 1½ miles from Kuskokwim Bay, and reached platiniferous gravel. This platinum was apparently localized in a pothole that was not eroded by the glacier, as no continuation of the deposit was found.

Platinum Creek, with a length of about 2 miles, has two tributaries from the north, called Fox Gulch and Squirrel Creek. These streams had paystreaks which extended from their headwaters to their mouths; and Platinum Creek was minable from the mouth of Fox Gulch to its confluence with Salmon River. The paystreak on Platinum Creek included stream placers and others that would more properly be classed as bench placers, though the two types were not distinctly defined. At the mouth of Fox Gulch, the width of this paystreak was 200 feet, and at the confluence with Salmon River it had a width of at least 400 feet. The depth to bedrock, less the surficial cover of moss, ranged going downstream from 12 to 25 feet. The total length of the paystreaks of Platinum Creek, Fox Gulch, and Squirrel Creek, was about 3½ miles. The platinum metals occurred in the lower few feet of the gravels, and on the surface of bedrock, and for a few feet within the cracks and crevices of fractured bedrock. These metals consist of fine grains, which, however, are larger than those recovered from the paystreaks of Salmon River. Nuggets are uncommon, though more prevalent in Fox Gulch than elsewhere. The largest nugget so far recovered had a weight of 4 troy ounces.

The platinum deposits in the valley of the Salmon River occur in two distinct paystreaks, one in the present valley floor and the other in what has been designated as the bench channel, along the eastern side of the valley. The valley paystreak extends from claim 7 above Discovery, near the mouth of Boulder Creek, downstream to the lower end of claim 15 below Discovery, a distance of about 6 miles. This deposit ranges in width from 300 to 450 feet, except at the mouth of Platinum Creek, where it was as wide as 600 feet. The bench paystreak, as defined by drilling, extends from the association claim east of claim 9 above Discovery downstream to within three-quarters of a mile from Chagvan Bay, a distance of about 10 miles. On the Olson bench claim, this deposit had a width of 600 feet, but at some sites farther upstream it was as wide as 1,000 feet.

The bench paystreak presents numerous problems of genesis and age. The average bedrock gradient is about 15 feet per mile greater than the bedrock gradient of the valley floor, so that the thickness of the bench deposit increases more rapidly than that of the valley floor. Thus, at the northern limit of the bench paystreak, the depth to bedrock was found to be only 15 feet; east of Discovery claim, the depth had increased to 45 feet; and at the lower end of the Olson bench claim, the depth had increased to 125 feet. At and opposite the upper part of claim 7 below Discovery, the altitudes of bedrock on the paystreaks of the bench and the valley floor are identical. The increasing thickness of overburden on the bench is a function of the higher gradient of bedrock, which in turn is related to the lower base level of erosion at the time when the bench paystreak was formed. Thus, bedrock attains the altitude of sea level about 4.8 miles from Chagvan Bay, whereas the bedrock of the valley floor attains the same altitude about half a mile farther downstream. At Happy Creek, the bedrock of the bench channel is 50 feet below sea level; and at a point seven-eighths of a mile from Chagvan Bay, a drill hole to bedrock has shown a depth of 200 feet below sea level. By projection, the depth at the north side of Chagvan Bay is about 250 feet below sea level. The counterpart of this profile is suggested by the cited drill hole on the north side of the road from Platinum to the Goodnews mining camp, about 1½ miles from Bering Sea, where bedrock was reached at a depth of 192 feet. On the other hand, the depth to bedrock at the mouth of Salmon River is only about 100 feet below sea level. Throughout the lower half of the bench paystreak, a large dragline excavator was used ahead of the dredge, to remove a part of the overburden, as the dredge could dig only to a depth of 60 feet. At the Olson bench claim, however, mining was temporarily discontinued, pending the development of new methods for the excavation and disposal of the increasing thickness of overburden.

The bench paystreak consists largely of clay from top to bottom, with an average content of about 20 percent gravel, which, however, is irregularly distributed vertically. Little sand and silt are present. The gravels occur mainly as inlaid seams and lenses in the clay, though in places drilling has penetrated beds of gravel ranging in thickness from 25 to 70 feet.

The pebbles and small cobbles that constitute the gravels are subangular to rounded, many are faceted, and the nonsiliceous ones are greatly decomposed. Many of the siliceous gravels occur as fragments that obviously represent broken parts of larger stones. Most of the gravels are coated with tightly adhering clay, similar to the cohesive semi-indurated interstitial clay; and in panning or mining, extensive scrubbing is required in order to loosen and disintegrate this clay, so that the included platinum metals may be made available for recovery. These alluvial materials, without doubt, were originally of glacial origin. It must also be recorded that although most of the alluvial materials in the Goodnews Bay district are free of permafrost, yet drilling on the lower (southern) end of the bench channel have revealed a number of frozen strata, some as thick as 20 feet.

The bedrock, if nonsiliceous, is deeply weathered, at places to a depth of 5 feet or more, so that in drilling it is often difficult to determine the upper surface of bedrock, particularly if it is directly overlain by clay. So soft is the bedrock that it can be shoveled and panned, and samples of mineral concentrates have been obtained by this procedures. The platinum metals occur mainly on the surface of bedrock and in the overlying 10 feet of clay and gravel; but if the bedrock has been shattered, platinum metals may also extend several feet into bedrock.

The fact that the surface of bedrock in the bench channel is nearly flat from side to side, with no incised channels, indicates continuous erosion at a nearly constant base level of erosion over a long period of time. This condition has made it possible for the ancient stream that occupied this channel to carve away the lower ends of the lateral spurs along its eastern side and thus expand the valley floor to its stated width. It is also of interest that the bench paystreak has been locally enriched in platinum metals at the sites of tributary gulches from the east that drained a still older paystreak higher on the valley wall. The sites of these ancient gulches, however, do not correspond exactly with the position of the gulches shown on the topographic map. These high-level deposits have been prospected, but have been found to be narrow, intermittent (due to erosion), and too low grade to be mined at a profit.

The platiniferous clay above bedrock is so cohesive that it does not disintegrate readily in the trommel screen of the dredge nor in the succeeding gigs and riffles, so that a serious loss in platinum metals has occurred in dredging. To test the magnitude of this loss, and to determine whether the bench gravels should be reworked, the Goodnews Bay Mining Co. built in 1966 an experimental rig, which they called a "mud-hog," to macerate this clay and its included and adhering gravels; and this operation yielded a profit in 1966 and 1967. In reworking the bench gravels, the dredge will have to be equipped with improved equipment for handling this kind of alluvial materials, either by crushing or washing them, or both.

The paystreak and channel in the present valley floor differ markedly from those of the bench. The paystreak is narrower, ranging from 300 to 450 feet, except at the mouth of Platinum Creek, where locally it is as wide as 600 feet. The overburden is shallower, ranging in thickness from 30 to 80 feet, and gravels constitute a larger part of the alluvium. The mean size of the gravels is also larger than those in the bench paystreak, ranging in size up to 2 feet or more in diameter. Clay, however, is entirely absent, with corresponding increments in the amounts of sand and silt. The cobbles and pebbles are fairly well rounded, but many of the larger gravels are subangular. Finally, the bedrock, which is quite unaltered by weathering, is not level, but instead shows deep gutters with a depth as great as 20 feet. The platinum metals occur mainly on bedrock, in the overlying 2 feet of gravels, and in the uppermost 2 feet of shattered bedrock. The sizes of the grains, diminishing downstream, range from 0.2 inch to less than 0.002 inch in diameter.

A significant feature of the creek paystreak is that it terminates, or at least becomes of noncommercial grade, at the lower end of claim 15 below Discovery. Equally significant is the fact that along the east bank of the Salmon River, just above the mouth of Happy Creek, there is an ancient deposit of fairly well sorted outwash gravels of glacial origin. Similar deposits are present in the sea cliffs, about a mile north of the mouth of the Salmon River. Clearly the paystreak from claim 15 below Discovery downstream was severed and eroded by an ancient glacier, probably of Illinoian age, that emerged from the valley of the Kinegnak River, riding high on the north wall of that valley, and crossing the valley of the Salmon River as it moved seaward. But the lower end of the bench paystreak, as earlier stated, appears not to have been similarly destroyed by glacial erosion. All the lithologic data indicate that the deposits of the bench channel are older than the basal gravels in the channel of the present valley, and it therefore seems probable that the bench paystreak was preserved because it rested on a bedrock floor much lower than that in the present valley. Intensive drilling is now in progress on the bench paystreak downstream from the Olson bench claim; and the preceding interpretation may be verified if the uppermost alluvium of the bench paystreak proves to be similar

to the gravels above the mouth of Happy Creek, and in the cited sea cliffs. Otherwise, the bench paystreak, old as it is, will have to be regarded as younger than the basal gravels of the valley paystreak. Under such an alternative interpretation, these basal gravels would probably be of Pliocene age, with other corrections in the genesis and age of the upper gravels of the valley floor.

Geochronology

The Pleistocene chronology, on the basis of available facts and inferences, can at best be only tentative, though a wealth of data that are now being analyzed and digested may later supply some of the missing links. Deposits of glacial origin have been found on the sea floor of Bering Sea, a long distance offshore from Nome; and the thickest and most extensive ice sheet that has overridden this region in Pleistocene time is believed to have existed in the first or Nebraskan Glaciation of this epoch. In the early Pleistocene, a great ice sheet appears to have nearly or quite overridden the hills that bound both sides of the valley of the Salmon River. Conceivably such an ice sheet may have developed either in Nebraskan or Kansan time, or even in both. In the absence, however, of conflicting data, the following chronology is based upon the existence of a single overriding ice sheet of Nebraskan age. As a result of this glaciation, the valley of the Salmon River must have received a large volume of morainal and glaciofluvial debris, most of which has subsequently been removed by erosion, though a part of it has been preserved in the bench channel along the east side of the valley. This is proven by the fact that no such materials now exist among the gravels that constitute the valley floor. Moreover, as earlier explained, an overriding ice sheet is a necessary part of the geochronology, in order to explain the presence of alluvial gold with the platinum metals in the upper valley of Platinum Creek.

The base level of erosion, at the apex of glaciation during Nebraskan time, was a strand line far south and southwest of Chagvan Bay. The mean gradient of the bedrock floor of the bench channel, from the center of the Olson bench claim to the north shore of Chagvan Bay, is known to be about 52 feet to the mile, such that the surface of bedrock at Chagvan Bay is now about 250 feet below sea level. The Nebraskan ice, which in its waning stages deposited glacial debris in the valley of the Salmon River, had an unrestricted outlet to the sea south and southwest of the Salmon Valley, and therefore must have greatly lowered the ancient base level of erosion. Hence even in the waning stages of Nebraskan glaciation, the local base level of erosion was much lower than at the present time. Thus, in late Nebraskan and early Aftonian time, a considerable part of the glacial debris in the Salmon Valley was eroded, but in part was preserved locally in the eastern bench channel. And eventually, with a rising base level of erosion, the bench channel was filled by aggradation. As a result, the course of the stream that occupied this channel was gradually shifted westward, and finally was superposed on bedrock at approximately the position of the present stream channel. The Aftonian Interglaciation, with a duration of approximately 200,000 years, was amply long to produce this aggradation and superposition.

The advent of the Kansan Glaciation, with or without local alpine glaciation, resulted in a new lowering of the base level of erosion. With a superposed drainage pattern already established, a new stream channel was carved under the control of a base level at least 100 feet lower than at the present time. This estimate is based upon the depth to bedrock at the mouth of the Salmon River. Another result was that all the remaining glacial debris of Nebraskan age was completely removed from the valley of Salmon River, except that preserved in the bench channel. In late Kansas time, and during the Yarmouth Interglaciation, the new channel was progressively filled with newly eroded gravels, and a paystreak was developed which extended much farther south than the paystreak of the present valley floor. This Kansan-Yarmouth erosion and subsequent sedimentation had virtually no effect upon the pre-existing bench channel, partly because erosion was in a new channel, but also because the lowering of the base level of erosion was distinctly less than that which prevailed in Nebraskan time.

The Illinoian Glaciation produced two significant results. The base level of erosion was again lowered, possibly in an amount intermediate between that which existed during Nebraskan and Kansan times. But in addition, active glaciation resulted in the development of ice tongues which emerged from the valley of the Kinegnak River, and from the valleys of the Goodnews River and its tributaries. Neither of these glaciers, however, moved down or up that part of the Salmon Valley enclosed by hills. The Kinegnak glacier eroded and dispersed such gravels as it could reach in the lower valley of the Salmon River, and in so doing, as earlier explained, severed and destroyed the lower end of the Kansan-Yarmouth paystreak. The effect of this transverse glaciation upon the bench gravels of the Salmon River has not yet been established, but the pre-existing bench paystreak was not obliterated, probably owing to the greater depth of its

underlying bedrock. The Illinoian ice from the valley of Goodnews River and its tributaries similarly extended into the upper valley of the Salmon River, and deposited morainal and outwash materials there, but did not move down that valley. Instead the ice was shunted seaward past the north side of the Red Mountain, leaving glacial erratics, however, on that mountain up to an altitude of 825 feet.

The glaciation during Illinoian time probably also caused another geomorphic result. At the height of this glaciation the Kinegnak and Goodnews glaciers may have completely blocked the valley of the Salmon River, thus producing an elongate lake, which not only prevented any appreciable run-off downstream (or upstream), but also impeded the transportation of fluvial sediments seaward. Erosion on the hills, however, did not cease, and the weathered debris was merely dumped into the lake, resulting in aggradation. Thus the lowering of the regional base level of erosion during Illinoian time was partly or wholly ineffective for the Salmon River. Even if a channel, continuous or intermittent, was maintained around the north end of the Kinegnak glacier, the result for the Salmon Valley would have been dominantly aggradation, rather than stream rejuvenation and the seaward movement of sediments.

The ensuing Sangamon Interglaciation, characterized by a rising base level of erosion, must have produced further aggradation in the valley of the Salmon River. Platinum metals continued to be added to the paystreaks of Platinum Creek and Salmon River, but a sluggish river did not serve to re-create the lower end of the Kansan-Yarmouth paystreak that had been severed by the Illinoian ice. Similar aggradation doubtless occurred in the valley of the Smalls River, producing a superposition of this stream onto the southern wall of its valley. The subsequent erosion by the Smalls River in Wisconsin time is believed to have produced the gorge that is now visible about 4½ miles from the mouth of this river.

Glaciation was prevalent in the Kigluaik and Bendeleben Mountains of Seward Peninsula, and in the Tikchik and Oklune Mountains northeast of Goodnews Bay during Wisconsin time. Moffit (1913) and Smith (1910), however, who mapped quadrangles at and east of Nome, believed that the Wisconsin ice did not extend to the present strand line of Bering Sea; and the same is probably true in the Goodnews Bay district. Therefore in so far as glacial erosion is concerned, the Wisconsin glaciers are believed to have been impotent in this district; but a pronounced lowering of the base level of erosion must have been highly effective in removing a large part of the sediments that had accumulated during Illinoian and Sangamon time. Platinum metals continued to be eroded from Red Mountain and deposited in the valley of Salmon River and its headwater tributaries from the west; but the paystreak, though doubtless enriched, was not extended downstream from the point of severance in Illinoian time. In other words, bedrock was not again uncovered, probably because all the energy of Salmon River was used in removing the accumulation of superincumbent sediments from the valley of the Salmon River.

The foregoing chronology has been formulated without recourse to faulting, which could have had an important effect upon the establishment of unrecognized changes in the base levels of erosion during the Pleistocene Epoch. Yet faulting, parallel to the coast, has been recognized in the search for submarine placers offshore from Nome. It follows that more geologic work is needed in the Goodnews Bay district, before all the known facts can be satisfactorily explained.

Platinum metals and gold

The occurrence of the platinum metals in the dunite of Red Mountain has been proven indirectly, though no platinum lodes have been discovered, and no samples of platinum-bearing bedrock have been found. Moreover, a composite of this dunite, taken from the south to the north end of Red Mountain, revealed by analysis no trace of the platinum metals. It should be emphasized, however, that the content of platinum metals in such a sample was probably too low to be detected by ordinary chemical analysis. If the sample had been milled and panned, an analysis of the resulting concentrates might have shown the presence of platinum. In this connection, it should be recorded that the residual material at one site on top of Red Mountain was sampled and concentrated in 1965 by the Goodnews Bay Mining Co. and was found to contain a small amount of the platinum metals.

The platinum metals of the placers occur essentially in two distinct alloys intergrown in a pseudoeutectic fabric, which in nuggets is clearly visible under a low-powered lens. These alloys do not have constant compositions nor do they have definite ratios to one another, and therefore they are not individually or collectively homogeneous. Moreover, the metals recovered from the placers, because they have been intermingled by stream transportation and fortuitous deposition, represent mixtures from many sites in the original lodes. Chemical analyses, however, of the metals recovered from the headwaters of the streams that drain Red Mountain, where maximum mixing

had not yet occurred, reveal certain general characteristics of the lodes. Moreover, these analyses, when charted by claims, reveal also significant data that have a bearing upon the regional physiographic history, and lead to an understanding of the sequential history of the two paystreaks in the valley of Salmon River.

The platinum metals at the south end of Red Mountain are distinctly higher in iridium and osmium than at the north end, as shown by numerous chemical analyses of these metals in the streams draining this mountain. Thus, the mean tenor of iridium and osmium on Fox Gulch, and on Platinum Creek downstream to the mouth of Squirrel Creek, are respectively 27.85 and 5.24 percents; on Squirrel Creek, the corresponding values are 15.49 and 3.93 percents; on Dowry Creek, these values are 7.49 and 1.49 percents; and on Clara Creek, they are 6.17 and 0.93 percents. No analyses of the platinum metals from Boulder Creek are available, and it is therefore impossible to state whether the change in composition from Platinum Creek to Clara Creek is or is not linear in relation to distance. It should also be mentioned that the maximum values of iridium and osmium found on Fox Gulch were respectively 41.06 and 8.41 percents. Yet this product fails to qualify as osmiridium, because of the high tenor in platinum, namely 47.20 percent. In reality, this and all other platinum metals found in this district represent intergrowths in various proportions of the ordinary platinum alloy and osmiridium. The product from Fox Gulch merely has the highest ratio of osmiridium to the more common alloy.

The physical properties of the two alloys doubtless differ materially, but these cannot be determined, because pure samples of these alloys cannot be obtained. The magnetic properties, however, are quite evident in bulk samples from the placers. Thus, 4 percent of a sample from Salmon River was found to be ferromagnetic, whereas 25 percent of a sample from Clara Creek was found to be ferromagnetic. This difference is doubtless related to the change in composition of the platinum metals, from the south to the north end of Red Mountain. That is, the ratio of the major to the minor alloy probably increases in this interval. All these platinum metals, however, are paramagnetic, though in varying degrees.

The compositions of the two alloys that contain the platinum metals have not been specifically determined, first because they are variable and second because, for reasons heretofore cited, it is impossible to obtain a pure sample of either alloy. Approximately, however, the minor alloy (osmiridium) may be separated electromagnetically, if grains of very small size are utilized in the separation. A sample weighing 365.53 grams, that represented platinum recovered in 1945 from Discovery claim, Salmon River, was used for this investigation. This was separated by sieving into 14 fractions; but unfortunately insufficient material of −200 mesh was available for a chemical analysis of that part of the sample with the smallest paramagnetism. One of the 14 fractions of larger size weighing 90.95 grams was therefore selected, and this was separated electromagnetically into seven subfractions. One of these subfractions, weighing 8.13 grams, with the least paramagnetism, was analyzed chemically, with separate analyses of the parts soluble and insoluble in aqua regia. Thus three analyses were obtained, as follows:

T. Composition of entire sample of 8.13 grams, wherein the ratio of the soluble to the insoluble fraction, $\frac{S}{I}=0.0375$.

S. Composition of that part of *T* soluble in aqua regia.

I. Composition of that part of *T* insoluble in aqua regia.

The selectivity of the separation is emphasized by the fact that the $\frac{S}{I}$ ratio of the original sample of 90.95 grams is 5.99, whereas this ratio for the subfraction *T* is only 0.0375. The three analyses are shown in table 34.

TABLE 34.—*Compositions, in percent, of electromagnetically separated alloy, and of its soluble and insoluble fractions, Goodnews Bay district*

	T	S	I
Platinum	14.48	93.50	11.52
Iridium	71.22	5.78	73.67
Osmium	11.00	.00	11.42
Ruthenium	1.15	.00	1.19
Rhodium	2.15	.72	2.20
	100.00	100.00	100.00

Sample *T* appears to be mainly osmiridium, and the absence of palladium is therefore to be expected, as this is generally true of osmiridium in other parts of the world. A small amount of the major alloy, however, is believed to be present in the sample. The osmium and ruthenium are insoluble in aqua regia, as shown by analyses *S* and *I*; but parts of the platinum, iridium, and rhodium are soluble. Reduced to grams, the $\frac{S}{I}$ ratios of platinum, iridium, and rhodium are found to be respectively 0.31, 0.0035, and 0.0046. Thus most of the iridium and rhodium in sample *T* is insoluble, whereas a third of the platinum is soluble. The $\frac{S}{I}$ ratio

is about 9.60, yet for the original sample of 90.95 grams, this ratio is about 11.89. Giving to these facts the most probable interpretation, it follows that analysis *I* approaches closely to the composition of the minor alloy (osmiridium), but the exact composition is not ascertainable. Parenthetically, these data illustrate how the solubilities of the platinum metals vary, depending upon whether they occur in alloys, or whether the pure metals are tested. They also show the difficulties that arise in attempting to obtain the true compositions of either or both alloys, even in a single sample.

A small amount of free gold is recovered with the platinum metals of the placers. The exact source of this is unknown, but it is thought to have originated in quartz veins associated with the granitic rocks at the head of the Smalls River. The proximate source of most of the gold are twofold. An early Pleistocene glacier, probably of Nebraskan age, overrode the valley of the Salmon River. It moved westward and deposited a large volume of glacial debris in this valley. Later, a glacier believed to have been of Illinoian age, moved down the valley of the Goodnews River, and spread out into the valleys of Tundra Creek and the Smalls River. Thus morainal and glaciofluvial materials were dumped at the head of the Salmon River, whence they later were moved down that valley by running water.

The gold in the valley of the Salmon River was derived both from the Nebraskan and the Illinoian glacial deposits. In the paystreak of the valley floor the amount ranges from 0.70 to 4.78 percent, with a mean value of 2.36 percent. In the bench paystreak, the amount is appreciably less, ranging from 0.57 to 4.79 percent, with a mean value of 1.35 percent. In the headwaters of Platinum Creek, notably on Fox Gulch, the amount of gold is very small, ranging from zero to 0.37 percent, with a mean value of 0.1 percent. It is believed that this gold was derived from a thin sheet of glacial or glaciofluvial debris that was deposited in this area by the overriding Nebraskan glacier.

The dross of platinum metals is rarely determined, as it is generally included with the residual black sand under the heading of "impurities." Actually such impurities include the alloyed dross of the platinum metals, a minor amount of silver and dross in the gold, extraneous metallic impurities such as solder and lead shot that have not been removed, minerals adhering to or included in the platinum metals, and black sand that was impracticable to remove from the final product. The dross of native gold, which generally is copper and iron, constitutes about 1 percent of the gold-silver alloy. The dross of the major platinum alloy is believed generally to consist of 8 to 10 percent of iron, copper, and nickel, rarely cobalt. Chromium, if it shows in an analysis, is probably not an alloyed metal, but comes from included chromite. Under the microscope, a few minute included crystals of chalcopyrite have been identified in the Goodnews product, so that even the copper and iron of the analysis of a picked sample may not be entirely alloyed metals, though they dominantly are such. The dross of the osmiridium in the Goodnews Bay placers has not been determined, but like that from the Urals and Colombia, probably consists of iron and copper, though in much smaller amounts than in the major alloy.

Some data on the character and amount of the true dross of these platinum metals were earlier published (Mertie, 1940, p. 80–81). These are given in table 35 as analyses A and B. In addition, Charles J. Johnston, of the Goodnews Bay Mining Co., later authorized Johnson, Matthey and Co., to make two complete analyses of platinum metals entirely free of black sand, from the Goodnews Bay district. These comprise analyses C and D. These four analyses, recomputed free of all constitutents other than the platinum metals and dross, are shown in the table 35. The dross shown in these analyses is the dross of mixed platinum and osmiridium, which is somewhat less than that of the major alloy, but much greater than that of the osmiridium alone.

TABLE 35.—*Analyses, in percent, of platinum metals showing dross, Goodnews Bay district*

	A	B	C	D	Mean
Platinum	57.84	82.25	77.07	77.09	73.56
Iridium	26.15	5.37	10.58	10.54	13.16
Osmium	5.71	.54	1.95	2.03	2.56
Ruthenium	.39	.28	.16	.16	.25
Rhodium	1.52	1.45	.94	.94	1.21
Palladium	.21	.14	.33	.35	.26
Iron	7.51	9.48	8.54	8.48	8.50
Copper	.40	.37	.43	.41	.40
Nickel	.27	.09	Tr.	Tr.	.09
Cobalt		.03			.01
Total	100.00	100.00	100.00	100.00	100.00

A. Fox Gulch, Discovery claim. (Mertie, 1940, p. 80, 81).
B. Clara Creek. (Mertie, 1940, p. 80–81).
C and D. Exact localities unknown, but believed to be from Salmon River. Analyses by Johnson, Matthey and Co.

A large volume of heavy minerals is recovered with the platinum metals. For example, a cleanup at one locality in the upper valley of Platinum Creek yielded 250 ounces of platinum metals together with 2 tons of concentrates, which were mainly magnetite, ilmenite, and chromite. The concentrates are classified, and the platinum metals are separated on a Wilfley concentrating table. The finest of this material still contains platinum and is ground and further concentrated. The platinum metals are finally cleaned by an ingenious vibrating blower. The final product that is sent to the refiner contains about 11 percent of impurities, of

which perhaps 8 to 10 percent is alloyed dross, showing that the removal of black sand by the Goodnews Bay Mining Co. is nearly complete.

One outstanding feature is the large amount of chromite recovered in the sluiceboxes during the placer mining. Nuggets have been found in which chromite is attached to or intergrown with the platinum metals; and these, together with the large volume of chromite recovered in the placer concentrates, led to the belief that many of the platinum metals are associated in bedrock with chromite. A similar condition exists in the Ural Mountains of Russia. In the largest body of dunite in the Urals, in the Nishniy-Tagil district, about 600 lenses and irregular masses of chromite have been found, some of which contained notable amounts of platinum, as heretofore described. A part of the platinum metals in the Goodnews Bay district, however, may be sparsely and widely distributed in bedrock. The mean tenor of platinum metals in the dunite of Red Mountain may be computed by comparing what was probably the original volume of that mountain with the total platinum metals so far recovered and recoverable in the future, plus the metals lost in mining operation. Such a computation yields a mean value of about 0.13 grain per cubic yard, which might have a value of about 3 cents per cubic yard. Obviously, only local concentrations of platinum in chromite, such as that in the Krutoy Log property in the Urals, are likely to be of economic interest.

Chemical analyses

Every cleanup of the dragline excavators and dredge of the Goodnews Bay Mining Co., since 1934, has been graded by sieving into eight fractions, ranging in size from plus 8 to minus 48 mesh; thereafter the output from each cleanup was sent to the refiner (Johnson, Matthey and Co., Inc.) at Malvern, Pa., though duplicate chemical analyses have also been made by the Griffith, Ledoux, and Baker companies. The sieving analyses since 1943, and all the chemical analyses since 1934, have been made available to the writer by the Goodnews Bay Mining Co. A few analyses of the product from Clara Creek, made by the Wildberg Smelting and Refining Co., were obtained from the Clara Creek Mining Co. The data obtained from the Goodnews Bay Mining Co. comprise 643 sieving analyses and 977 chemical analyses.

A second source of information needs to be mentioned. From the 25th cleanup of 1945, the writer obtained from Charles J. Johnston, treasurer of the Goodnews Bay Mining Co., a sample of 365.53 grams, that included 321.84 grams of platinum metals, a little gold, and about 10.75 percent dross. This sample was taken to Malvern, Pa., where it was opened and sieved in the presence of John Cochrane, then chief chemist, but now a vice president of the American branch of Johnson, Matthey and Co., Inc. The sample was divided by sieving into 14 fractions, and the largest of these was subsequently subdivided into seven other fractions, which were separated from one another electromagnetically. Under the supervision of Mr. Cochrane, these 20 fractions were separated into dual subfractions, soluble and insoluble in aqua regia, and 40 complete analyses were made by E. R. Johnson, a chemist in the employ of Johnson, Matthey and Co., Inc. The expense of this work was born jointly by the Goodnews Bay Mining Co. and by Johnson, Matthey and Co., to both of whom the writer is greatly indebted. The three analyses shown in table 34 are based upon a part of these results.

A third source of information has been annual statements since 1934 by Charles J. Johnston, treasurer of the Goodnews Bay Mining Co., of the yearly production of the six platinum metals and gold, together with the weights of dross and other impurities as determined by chemical analyses. From 31 of these statements, omitting those of 1934 and 1935 of doubtful accuracy, it has been possible to construct two tables, 36 and 37, wherein are given, respectively, the annual percentages of the platinum metals, gold and impurities, and of the platinum metals free of gold and impurities.

TABLE 36.—*Percentages of platinum metals, gold, and impurities, Goodnews Bay district*

[Based on data from Goodnews Bay Mining Co.

Year	Pt	Ir	Os	Ru	Rh	Pd	Au	Impurities
1936	68.30	12.72	3.24	0.24	1.46	0.23	0.45	13.27
1937	64.95	17.28	3.29	.29	1.85	.25	1.08	11.01
1938	72.19	11.24	2.24	.17	.99	.29	1.60	11.19
1939	71.54	12.26	2.57	.20	1.16	.31	1.63	10.33
1940	71.77	12.34	2.56	.19	1.16	.32	1.80	9.86
1941	72.44	11.06	2.22	.20	1.14	.3	2.01	10.63
1942	72.50	10.37	2.14	.16	1.31	.34	2.73	10.43
1943	74.66	9.30	1.75	.13	1.21	.36	2.19	10.29
1944	74.67	9.65	1.82	.14	1.21	.37	2.13	10.01
1945	73.09	10.30	2.07	.16	1.31	.34	2.16	10.57
1946	76.24	7.61	1.42	.10	1.12	.39	2.91	10.21
1947	77.25	5.83	.94	.07	1.01	.38	3.73	10.79
1948	77.47	6.20	1.01	.08	1.04	.30	2.83	10.98
1949	76.86	7.07	1.22	.10	1.14	.38	2.54	10.69
1950	75.46	9.13	1.50	.14	1.23	.35	1.64	10.46
1951	75.26	9.33	1.76	.14	1.28	.35	1.43	10.45
1952	73.23	11.10	2.15	.18	1.30	.33	1.32	10.39
1953	71.57	12.19	2.45	.19	1.21	.31	1.46	10.62
1954	73.31	10.91	2.02	.17	1.19	.34	1.37	10.69
1955	74.39	9.83	1.76	.16	1.31	.38	1.69	10.48
1956	76.19	8.27	1.10	.10	1.16	.37	1.67	11.24
1957	75.39	8.26	1.42	.11	1.12	.38	1.70	11.62
1958	75.03	7.96	1.25	.11	.98	.33	1.70	12.64
1959	75.22	7.88	1.40	.11	.95	.32	1.98	12.14
1960	75.64	7.85	1.34	.11	.89	.36	1.54	12.27
1961	76.19	7.42	1.28	.10	.96	.37	1.68	12.00
1962	76.16	7.22	1.25	.10	.96	.37	1.82	12.12
1963	71.83	10.18	1.93	.15	.98	.33	2.52	12.08
1964	69.42	11.92	2.38	.19	1.00	.29	3.11	11.69
1965	69.80	12.26	2.41	.19	1.01	.29	3.34	11.60
1966	67.62	12.99	2.56	.19	1.04	.28	3.85	11.57
1967	67.51	12.60	2.59	.18	.98	.27	4.17	11.70
Weighted means	73.62	9.94	1.90	.15	1.15	.34	2.06	10.65

TABLE 37.—*Percentages of platinum metals, Goodnews Bay district*

[Based on data from Goodnews Bay Mining Co.]

Year	Pt	Ir	Os	Ru	Rh	Pd
1936	79. 26	14. 74	3. 76	0. 28	1. 69	0. 27
1937	73. 88	19. 66	3. 74	. 33	2. 11	. 28
1938	82. 86	12. 91	2. 57	. 19	1. 13	. 34
1939	81. 25	13. 93	2. 92	. 23	1. 31	. 36
1940	81. 25	13. 97	2. 89	. 22	1. 31	. 36
1941	82. 92	12. 65	2. 54	. 22	1. 31	. 36
1942	83. 48	11. 94	2. 46	. 19	1. 51	. 42
1943	85. 33	10. 73	2. 00	. 15	1. 38	. 41
1944	84. 99	10. 98	2. 07	. 16	1. 38	. 42
1945	83. 75	11. 80	2. 37	. 19	1. 50	. 39
1946	87. 76	8. 76	1. 63	. 12	1. 28	. 45
1947	90. 38	6. 82	1. 09	. 08	1. 18	. 45
1948	89. 89	7. 19	1. 17	. 09	1. 20	. 46
1949	88. 58	8. 14	1. 40	. 12	1. 32	. 44
1950	85. 85	10. 39	1. 80	. 16	1. 40	. 40
1951	85. 40	10. 59	2. 00	. 16	1. 46	. 39
1952	82. 94	12. 57	2. 43	. 21	1. 47	. 38
1953	81. 40	13. 87	2. 78	. 21	1. 38	. 36
1954	83. 36	12. 40	2. 30	. 20	1. 35	. 39
1955	84. 70	11. 19	2. 00	. 18	1. 50	. 43
1956	87. 39	9. 48	1. 26	. 11	1. 34	. 42
1957	86. 97	9. 53	1. 64	. 13	1. 29	. 44
1958	87. 59	9. 29	1. 46	. 12	1. 15	. 39
1959	87. 59	9. 17	1. 63	. 12	1. 11	. 38
1960	87. 77	9. 11	1. 55	. 12	1. 03	. 42
1961	88. 27	8. 59	1. 48	. 12	1. 11	. 43
1962	88. 49	8. 39	1. 45	. 12	1. 12	. 43
1963	84. 11	11. 92	2. 26	. 17	1. 15	. 39
1964	81. 47	13. 99	2. 79	. 22	1. 18	. 35
1965	81. 00	14. 41	2. 83	. 23	1. 19	. 34
1966	79. 94	15. 24	3. 03	. 23	1. 23	. 33
1967	80. 25	14. 98	3. 08	. 21	1. 16	. 32
Weighted means	84. 53	11. 42	2. 17	. 17	1. 32	. 39

Table 36 shows the percentages of the platinum metals, gold, and all impurities. Silver that was reported in a few of these analyses is alloyed with gold, and in table 36 is included as a part of the dross. Table 37 shows the platinum metals alone, recomputed to total 100 percent. The means at the foot of each column in both tables have been computed, not from the annual percentages, (which would be improper), but from the actual weights of the metals produced and are therefore equivalent to weighted mean values. From no other platinum field in the world is it possible to state with precision the actual composition of the metals that characterize that particular field.

The analytical data cited in tables 36 and 37 yield a number of conclusions regarding the composition and distribution of the platinum metals and alloys in bedrock, and also interpretations of the genesis and chronology of the two paystreaks in the valley of the Salmon River. These data will not be analyzed exhaustively in this report, but one generalization bearing upon the composition of the platinum metals in these two paystreaks should be mentioned. The crux of all these problems is the variable ratio of iridium to platinum in the platinum alloys of the ultrabasic mass if that constitutes Red Mountain. As earlier stated, iridium is the most prevalent at the southern end of this mountain, and least so at its northern end. Consequently, if the analyses of the platinum metals are charted claim by claim in the valley of the Salmon River, it is found that iridium increases and platinum decreases in both paystreaks, from their upper ends downstream to the mouth of Platimum Creek. Downstream from Platinum Creek, the amount of iridium in the paystreak of the valley floor continues to increase, rising to 15½ percent of the total platinum metals on claim 11 below Discovery. Parenthetically, this value approaches the mean value of 18 percent that characterizes the placers of Platinum Creek, between the mouth of Squirrel Creek and the Salmon River. In the bench paystreak, however, after a marked increment at the mouth of Platinum Creek, the amount of iridium decreases downstream, diminishing finally to 8½ percent on the Olson bench claim. Inversely, the percentages of platinum in the two paystreaks change respectively to 79½ and 88 percent. In general, the percentages of osmium and ruthenium correlate closely with those of iridium.

The bench paystreak has obviously received more of the platinum metals that originated in that part of Red Mountain north of Squirrel and Platinum Creeks, and conversely, a major part of the platinum metals in the paystreak of the valley floor came from the southern end of Red Mountain, via Platinum Creek and its left limit tributaries. It is not entirely clear, however, whether this condition is a result of peculiar physiographic processes, or whether it is a function primarily of time. If, as heretofore stated, the paystreak of the valley floor is of composite origin, it is more probable that the high-iridium content in this paystreak may be dominantly a function of time, though other contributing causes will also require examination and evaluation. The volume of platinum metals in each paystreak, and other information deductible from the cited data, may yield more definite conclusions.

OTHER ALASKAN DEPOSITS

Alluvial platinum metals have been found to be widely distributed in Alaska, and prior to the discovery of the placers of Goodnews Bay district, they had been identified in alluvial deposits at about 20 localities. All these occurrences consisted of small amounts of the platinum metals found in gold placers, and none of these deposits became significant producers of platinum. These occurrences have been described by Chapin (1919, p. 137–141), Harrington (1919, p. 339–351, p.

369–400), Maddren (1919, p. 229–319), and Mertie (1919, p. 233–264; 1933, p. 134–135). The recognized localities are as follows:

Central Alaska

Granite Creek, Ruby district
Boob Creek, Tolstoi district

Southern Alaska

Kahiltna River, tributary Yentna River
Cache Creek, tributary Kahiltna River
Willow Creek, Cache Creek district
Poorman Creek, Cache Creek district
Long Creek, Cache Creek district
Slate Creek, Chistochina district
Miller Gulch, Chistochina district
Metal Creek, Kenai Peninsula
Lituya Bay, beach deposit
Kodiak Island, beach deposit

Southwestern Alaska

Arolic River, lower Kuskokwim area
Snow Gulch, tributary Arolic River, lower Kuskokwim area
Bear Creek, tributary Tuluksak River, lower Kuskokwim area
Butte Creek, tributary Faro Creek, tributary Arolic River, lower Kuskokwim area
Marshall district, several localities, lower Yukon area

Seward Peninsula

Dime Creek, Koyuk district
Bear Creek, Fairhaven district
Sweepstakes Creek, Fairhaven district

Cache Creek is an eastern tributary of the Kahiltna River, which flows to the Yentna River, of southern Alaska. Traces of gold and platinum were panned on the bars of Kahiltna River, but the valley of this stream had no placers. On Cache Creek, however, and on a number of its tributaries, workable placers were found. A dredge which operated on Cache Creek in 1917 and in subsequent years commonly recovered about a level teaspoonful of platinum with each cleanup, and this probably represents the maximum production from any one site. The writers estimated that the platinum metals constituted about 0.3 percent of the gold by weight. Small amounts of platinum metals were also found in the upper tributaries of the Tokichitna River which head against Cache Creek. All these streams are in an intensely glaciated part of Alaska so that the bedrock sources of the gold and platinum are unknown.

Dime Creek, on Seward Peninsula, was one of the better known localities where the platinum metals were found in gold placers. The tenor was estimated by Harrington at 1 ounce per $5,000 in placer gold, which, when the price of gold was $20.67 per fine ounce, amounted to about that found on Cache Creek. During the season of 1917, 35 ounces of platinum metals was produced on Dime Creek. Another small producer was Boob Creek, in the Tolstoi district, where 30 ounces was reported to have been sold, but not necessarily produced, in 1917. The valley of Dime Creek and the other tributaries of the Koyuk River were not overridden by Wisconsin ice, but the bedrock sources of the platinum metals have not been definitely recognized. The same is true for Boob Creek, and the placers of the Ruby district, though a type of bedrock has been recognized that could have supplied platinum metals.

The production of placer platinum overlaps in time the lode production from the Salt Chuck mine, in southeastern Alaska, and as the two kinds of production were combined in the statements of the Geological Survey after 1917, no satisfactory estimate of annual or total placer production can be given, though the recorded annual production began with 8⅓ ounces in 1916, and was reported by Brooks (1922, p. 23) to have been 53.4 ounces in 1917. The gold placers of Snow Gulch, Bear Creek, and Butte Creek were prospected and by the Goodnews Bay Mining Co., but the platinum that was recovered was added to that produced in the early years of mining in the Goodnews platinum placers.

Chemical analyses

Four analyses of the platinum metals of Alaska were made in the laboratory of the U.S. Geological Survey by R. C. Wells, and published by Harrington (1919a, b), Maddren (1919), and Mertie (1919). In addition, three superior analyses were made by Johnson, Matthey and Co., at the request of the Goodnews Bay Mining Co., of the platinum metals from the Snow Gulch, Bear Creek, and Butte Creek. Ruthenium was not determined in the U.S. Geological Survey analyses, and a considerable part of the iridium was not separated from the osmium. These analyses, recomputed free of impurities to total 100 percent, are shown in table 38.

These analyses are highly variable in their contents of the six platinum metals. The combined contents of iridium and osmium in samples C, D, E, F, and G range from 17 to 47 percent, but samples E, F, and G are much higher in ruthenium than any samples from the Goodnews Bay district. The analysis of sample C bears some resemblance to the analyses of the samples from Fox Gulch, in the Goodnews Bay district. Analysis A appears to represent a single platinum alloy, wherein the other elements are scantly represented. Analysis B may represent a major platinum alloy mixed or intergrown with a small amount of osmiridium, but the percentages are too indefinite to

TABLE 38.—*Analyses in percent of Alaskan placer platinum metals*

[N.D., no data]

	A	B	C	D	E	F	G
Platinum	98.1	88.8	51.4	64.8	76.32	72.82	59.07
Iridium	.5	4.7	12.3	10.0	8.34	15.56	15.38
Iridium plus osmium	.7	4.3	34.8	24.2			
Osmium					8.34	8.17	14.82
Ruthenium	N.D.	N.D.	N.D.	N.D.	5.05	2.29	9.31
Rhodium	.4	1.1	1.5	.9	1.26	.78	.96
Palladium	.3	1.1	Tr.	.1	.69	.36	.46
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0

A. Boob Creek, Tolstoi district, central Alaska. Analyst, R. C. Wells (Harrington, 1919a, p. 350).
B. Dime Creek, Seward Peninsula. Analyst, R. C. Wells (Harrington, 1919b, p. 396).
C. Poorman Creek, tributary Peters Creek, Cache Creek district, southern Alaska. Analyst, R. C. Wells (Mertie, 1919, p. 258).
D. Canvas Point, west coast of Kodiak Island. Analyst, R. C. Wells (Maddren, 1919, p. 316).
E. Snow Gulch. Analysis, Johnson, Matthey and Co.
F. Bear Creek. Analysis, Johnson, Matthey and Co.
G. Butte Creek. Analysis, Johnson, Matthey and Co.

draw any certain conclusions. Analyses C to G, inclusive, definitely represent mixtures or intergrowths of two alloys, one mainly platinum and the other osmiridium. For samples E to G, inclusive, this conclusion is fortified by the relatively high percentages of ruthenium.

PLATINIFEROUS PLACER GOLD

A terrestrial formation of Tertiary age crops out south of the Yukon River in Alaska and extends from the international boundary N. 60° W. for about 90 miles. East of the international boundary, these rocks extend into Canada for an undetermined distance. This belt ranges from a width of 2 miles or less at the boundary to as much as 13 miles in the valley of Seventymile River, south of Eagle. At its western limit, the belt thins considerably, and west of Thanksgiving Creek is overlapped by unconsolidated alluvial deposits of Pliocene and Pleistocene age.

A batholith of granitic rocks crops out south of the terrestrial belt at distances ranging from 4 to 15 miles; and from quartz veins and other sources related to the granitic rocks much native gold has been liberated by weathering and erosion. The granitic rocks and their lodes are believed to be of Mesozoic age but were bared to erosion in early Tertiary time, and the gold from the related lodes was transported northward by streams and deposited in beds which later were indurated to form parts of the terrestrial formation. This Tertiary formation thus became a proximate source of native gold, and many of the valleys of streams that flow northward from these rocks contain gold placers which exist both as terrace deposits and as younger deposits in the present valley floors. The principal streams whose valleys have gold placers derived from such sources are, named from east to west, American Creek, Wolf Creek, Mission and Excelsior Creeks, several south-flowing tributaries of the Seventymile River, a small stream called Fourth of July Creek that flows northward to the Yukon River, Washington Creek, Webber Creek, and Thanksgiving Creek. The regional and economic geology of the granitic rocks, the terrestrial formation, and the placers derived therefrom have been described by the writer (1937, p. 251-261, and 1942, p. 213-264) in two earlier publications.

None of the gold placers that originated in the manner above described contains the smallest trace of free platinum metals. Nevertheless, three samples of the placer gold were selected by the writer for complete analyses, with special reference to any content of alloyed platinum metals. This work was done in the laboratory of the U.S. Geological Survey by R. E. Stevens. The resulting analyses recomputed to total 100 percent, together with their localities, are shown in table 39.

TABLE 39.—*Analyses, in percent of placer gold, Yukon Valley, Alaska*

	38 A Mt 27	38 A Mt 57	38 A Mt 90a	Mean
Gold	81.13	88.23	93.17	87.51
Silver	18.33	11.21	6.19	11.91
Platinum	.20	.28	.42	.30
Iridium	.02	.05	Tr.	.02
Rhodium	None	None	None	None
Palladium	None	Tr.	None	Tr.
Lead	.06	.07	.08	.07
Mercury	.10	.05	.02	.06
Iron	.08	.07	.07	.07
Copper	.03	.01	04	.03
Zinc	.04	.03	.01	..03
Cobalt	None	None	None	None
Nickel	None	None	None	None
Bismuth	None	None	None	None
Tin	Tr.	Tr.	Tr.	Tr.
Total	100.00	100.00	100.00	100.00

38 A Mt 27. Seventymile River, at mouth of Broken Neck Creek. Analyst, R. E. Stevens
38 A Mt 57. Fourth of July Creek, 7 miles airline from mouth. Analyst, R. E. Stevens.
3 A Mt 90a. Woodchopper Creek, 4 miles airline from mouth. Analyst, R. E. Stevens.

These analyses represent three grades of native gold, having finenesses respectively of 811, 882, and 932. Sample 38 A Mt 90a, with gold of the highest grade, contained the largest amount of platinum metals. This highgrade gold was being mined in large volume in 1938 by a dredge, and the operators, when informed by the writer of the content of platinum metals in their product, tried to recover payment for the same. Payment, however, was refused, because the United States mint claimed the platinum metals as seignorage. Thereupon the operators took steps to recover the value of the platinum metals by having them separated from the gold before the latter was sold. This yielded an increment in gross profit of about 1.3 percent, from which, however, the cost of the pretreatment of the gold had to be deducted.

This occurrence of platinum metals in native gold is not unique, as similar gold has been mentioned by others, but it probably is one of the best authenticated quantitatively. On page 98 of this report are described certain rare deposits of gold quartz veins which have also yielded small amounts of the platinum metals. It is also known that significant amounts of the platinum metals are recovered in the refining of gold and copper. From these considerations, it follows that the native gold containing small amounts of alloyed platinum metals may be more commonplace than is generally recognized.

EXPLORATION IN ALASKA

The platinum metals have been shown to exist at many widely separated sites in Alaska, and one workable lode and one important placer deposit have been developed. These occurrences should offer encouragement for a careful search throughout the State for new deposits. It is true that a great deal of prospecting has been done in Alaska, but this work has had for its principal objective the discovery of gold placers. Native platinum could readily be overlooked in panning streams for gold, as the ordinary prospector might not have been impressed by the presence of steely looking grains in his gold pan. This apparently was true in the Goodnews Bay district, as this area was well known and accessible to prospectors for at least 25 years before the initial discovery of platinum was made. Therefore, such earlier prospecting by men searching primarily for gold must be greatly discounted.

The search for platinum lodes, however, is a project that requires understanding of the difficulties involved and may be beyond the capabilities and resources of ordinary prospectors. Platinum-bearing lodes, such as those of Canada, South Africa, and Siberia, are generally deposits of sulfides of copper and nickel. Those sulfides, if not destroyed by weathering, could be recovered in concentrated form by panning alluvial deposits; and if they are thought to be platinum-bearing, may be submitted for analysis. On the other hand, if the sulfides have been destroyed by weathering, the liberated platinum minerals, because they are so fine grained, are likely to have been floated by water and to have been widely distributed far downstream. If the platinum metals are chemically combined with the sulfides, the scattering is still more diffuse. Hence, the gold pan has a limited adaptability in prospecting for platinum lodes.

Small samples of bedrock will not be useful for analysis, because the platinum metals are so sparsely and widely disseminated, both as native platinum and platinum minerals, that such analyses will be undependable. Large samples of bedrock will be needed, and in a country like Alaska, these will have to be transported long distances to get them to a laboratory where they can be crushed, milled, and concentrated prior to analysis. Bearing in mind these obstacles and safeguards and the lack of cheap transportation throughout most of Alaska, it is not surprising that the search for platinum lodes in this State has so far been unsuccessful. Finally, analyses for the platinum metals should not be attempted by an ordinary assayer or chemist; in fact, assayers of excellent reputation have failed in such work. Instead, the samples should be submitted to processors of the platinum metals, or to others who are familiar with the chemical methods required. Superior analyses for the platinum metals are very expensive, and for this reason, the prospecting for platinum lodes will have to be done by mining companies with adequate financial backing.

Geologic maps on reconnaissance or exploratory scales are now available for most of Alaska, and more detailed maps are locally available. Ultrabasic and gabbroic rocks, the hostrocks of most of the platinum metals, will appear on these maps, and such rocks will serve as a first guide to concerns that are financially able to undertake prospecting for platinum metals. One example of an area that should be prospected is in the Yukon-Tanana region, of interior Alaska, where ultrabasic and basic rocks crop out intermittently for a distance of about 90 miles from the headwaters of Salcha River west-southwestward to the Tanana River, about 25 miles southeast of Fairbanks. Similar examples may be found in other parts of Alaska. Most of these projects will require the use of helicopters.

CALIFORNIA

Bodies of peridotite and serpentinite are present in California, and some of these have been cited as bedrock sources, though not all are well authenticated. One of these is in San Bernardino County where platinum was reported with lead carbonate at a mine near Cima. A second was the occurrence of platinum in chromite ore in Del Norte County. A third was the reported occurrence of platinum in serpentinite in the valley of Trinity River. A fourth was the reported discovery of traces of platinum in peridotite in the Santa Lucia Mountains in San Luis Obispo County.

PLACERS

Alluvial platinum has been found at numerous localities in California in association with native gold, and a small production has resulted as a byproduct of gold placer mining. Such mining has been done in two general districts. The largest and most productive of

these, both in gold and platinum, is the piedmont district west of the Sierra Nevada Mountains, that extends from Plumas County south-southeast for about 210 miles to include Merced and Mariposa Counties, with a width ranging from 30 to 65 miles. Other scattered localities lie farther to the west, south, and southeast. The second principal area is the Klamath district, which from the northwestern corner of the state extends south-southeast for about 170 miles to Tehama County, with a width of about 40 miles.

The 21 counties of these two areas are listed alphabetically below, and the 15 which have been productive are indicated by an asterisk.

Platinum-bearing counties of the piedmont area

1. *Amador	9. Plumas
2. *Butte	10. *Sacramento
3. *Calaveras	11. San Joaquin
4. El Dorado	12. Sierra
5. Mariposa	13. *Stanislaus
6. *Merced	14. Tuolumne
7. *Nevada	15. *Yuba
8. *Placer	

The scattered localities west, south, and southeast of the Sierra district are in Inyo, Kern, Madera, Riverside, San Bernardino, and Yolo Counties. None of these has been productive.

Platinum-bearing counties of the Klamath district

1. *Del Norte	4. *Siskiyou
2. *Humboldt	5. *Tehama
3. *Shasta	6. *Trinity

Platinum metals also occur along the Pacific beaches from Ventura County northward to and beyond the California-Oregon line. These counties containing littoral deposits, named from south to north, are as follows:

1. Ventura	6. San Mateo
2. Santa Barbara	7. Mendocino
3. San Luis Obispo	8. Humboldt
4. Monterey	9. Del Norte
5. Santa Cruz	

Platinum has also been found inland from the beaches in San Luis Obispo and Mendocino Counties, and Mendocino County has been a producer from such a source.

DEPOSITS

Most of the platinum recovered in California has been and is being produced as a byproduct of gold placer mining in the piedmont and Klamath districts, though a small production came in earlier years from beach mining, particularly from Humboldt and Del Norte Counties. The piedmont district, owing to its geographic environment, has been the largest and most consistent producer. The eastern tributaries and sub-tributaries of the Sacramento River head in the Sierra Nevada and debouch onto low foothills with broad valleys of low gradients that are especially adapted to dredging. Such sites of dredging, named from north to south, are the valleys of Feather River, Yuba River, lower and upper American River, Cosumnes River, Mokelumne River, Calaveras River, Stanislaus River, Tuolumne River, and Merced River.

The Feather River valley was the first site of large-scale dredging in California, which was begun in the vicinity of Oroville. The paystreak was originally determined to have a length of 7 miles and an average width of over a mile, but this was probably extended in later days of mining. Drilling has shown no bedrock to a depth of 500 feet, so that the section includes 6 to 16 feet of soil, underlain by auriferous gravel with a thickness of 20 to 50 feet, underlain by grayish volcanic ash which functions as a false bedrock. Most of the precious metals occur low in the gravel, close to the layer of ash. The ratio of gold to platinum metals is reported to be about 1,000:1, and the ratio of platinum to osmiridium is given by Logan (1919, p. 21) as approximately 10:3.

The valley of the Yuba River is similar in most respects to that of Feather River. The overburden varies in depth from 45 to 100 feet, and the pay gravel rests similarly on volcanic ash. The fact that platinum decreases more rapidly than gold in the downstream part of the paystreak indicates that the grains of platinum are probably larger. The ratio of gold to platinum metals ranges from 500:1 to 2,500:1. It is stated by Logan (1919, p. 21) that platinum constitutes 62 to 69 percent of the platinum metals and that the sum of iridium and osmium is 15 percent, of which iridium is much more plentiful than osmium. The conditions on the Feather and the Yuba Rivers are fairly typical of those in the valleys farther south, except for differences in stratigraphic sections, ratios of gold to platinum metals, and the composition of these metals.

The Klamath district differs from the Sierra Nevada district in that it consists largely of mountains, with streams of high gradients that flow in narnarrow valleys. The Klamath, Siskiyou, Trinity, and other coastal ranges make up the mountainous areas. Siskiyou, Trinity, and part of Humboldt Counties are drained by the Klamath River and its tributaries; Shasta and Tehama Counties lie within the watershed of the Sacramento River; and Del Norte County is drained by the Smith River and its several forks. The Klamath is a stream with many tributaries, of which the largest is the Trinity River; a smaller tributary,

in which much placer mining was done, is the Salmon River, which enters about 20 miles upstream from the mouth of the Trinity River. Both stream and terrace deposits constitute the workable placers of the Klamath district, and owing to the topography, most of these have been worked by hydraulic methods. One of the well-known terrace deposits of the Smith River is French Hill, between its South and Middle Forks, at an altitude of 2,000 feet; but many stream and low terrace deposits have been worked in the tributaries of the Smith River.

Considerable gold placer mining was done at numerous sites in the valley of the Klamath River, and one dredge was operated on a southern tributary called Scott Creek. The principal mining, however, was done on the Trinity River and its tributaries, particularly upstream from its North Fork. In the headwaters of Trinity Creek is Hayforth Creek, which is well known as a producer of gold. The two headwater tributaries of Hayforth Creek head against Beegum Creek, a headwater stream of the Sacramento drainage system, which is a well-known producer of Tehama County. The valleys of the Trinity River and its tributaries have many terrace deposits at different altitudes, some of which have been highly productive; and its valley floor has important stream placers. At least two dredges and numerous hydraulic plants have worked the stream placers of the Trinity River. The upper valley of the Trinity River is well known for the presence of large nuggets of platinum, but unfortunately no precise chemical or mineralogical investigations of these nuggets were made.

Platinum has been found on the Pacific beaches of California intermittently from Ventura County northward to and beyond the California-Oregon line, but the principal mining operations have been in the vicinities of Gold Bluff, Big Lagoon, Stone Lagoon, and Little River, in Humboldt County; and near Crescent City, Gilbert Creek, and Smith River, in Del Norte County. Mining began at Gold Bluff in 1851 and continued at other sites during the fifties and sixties but was most active from the middle of the seventies until the deposits were exhausted. Most of these operations were along the present beach, but terrace deposits were also found farther inland, though these were generally of lower grade. Few data are available concerning the character of the platinum alloys but five analyses of the platinum metals from the beaches of Humboldt County are given in table 40 (analyses 1–5). It also is recorded by Hornor (1918, p. 35–37) that the semiheavy minerals found near Crescent City consisted mainly of magnetite, ilmenite, chromite, garnet, monazite, olivine, apatite, picotite, rutile, and corundum.

The earliest production of placer platinum in California has not been recorded, but Quiring (1962, p. 254) cites an output of 656 crude ounces in 1880. According to Symons (1943, p. 49) the total production of platinum metals from 1887 to 1941, inclusive, was 22,520 ounces, with a maximum output of 1,358 ounces in 1940, and a minimum output of 39 ounces in 1903. These figures represent crude ounces for the interval 1887–1918 and fine ounces for the interval 1919–41. Hence, the total output for the period 1887–1941 must be less, perhaps 1,000 to 1,500 ounces less, than the cited total. Moreover, a declining production of placer gold in California since the Second World War has further diminished the output of platinum metals. Considering all factors involved, it is believed that the total output to 1963 has not exceeded 30,000 ounces.

CHEMICAL ANALYSES

The placer mines of California are like those at other places in the world where platinum metals were or are being produced as a byproduct of gold mining. Little attention is given to the composition of these metals, and most of the analyses are rather crude commercial assays, of which some were made by nonqualified analysts. In such assays, iridium and osmium are rarely reported separately; and except in osmiridium, ruthenium is altogether ignored. One cause of this in the early days of mining was that osmium was not even bought, and hence was not reported. The available data thus constitute a problem in their presentation. If reported as given, the different analyses are hard to compare; but if recomputed to total 100 percent, it is certain that the tenors of the reported elements are unjustifiably increased by the distribution in them of the unreported elements. Neither method is correct, but the second seems to represent the lesser of two evils, and is used in table 40.

The localities of the available analyses, so far as they are known, are given in the table. Some analyses are given as averages. Others, such as 1–5, are given individually; first, because the tenors in platinum are strongly variable, and second, in order to show tenors in iron and copper, which are not generally available in the other analyses.

A considerable number of analyses of the platinum metals, more incomplete than the preceding ones, have also been published by Logan (1919, p. 109) (table 41). These, however, have considerable value in that they show general variations in composition from county to county.

The analyses (tables 40 and 41) show two characteristics possessed by the platinum metals of California. First, a great variation exists in the compositions of

Table 40.—*Analyses, in percent, of California placer platinum metals*

[N.D., no data]

	1	2	3	4	5	6	7	8	9
Platinum	87.78	82.45	79.07	63.87	58.33	74.09	80.56	19.06	27.90
Iridium	1.08	4.34	.88	.71	3.13	2.02	2.18		30.21
Osmium		.05	1.29		.82	.72	.47		28.60
Osmium plus iridium	1.13	5.11	7.80	22.75	27.93	12.91	14.12	80.94	
Ruthenium									12.52
Rhodium	1.03	.67	2.02	1.82	2.48	1.60	1.75		.75
Palladium	.61	2.01	1.34	.10	.25	.86	.92		.02
Iron	6.93	4.60	6.31	6.46	6.86	6.21			
Copper	1.44	.77	1.29	4.29	.20	1.59			
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

	10	11	12	13	14	15	16	17
Platinum	21.28	44.75	N.D.	95.80	94.02	60.62	91.17	95.85
Iridium	.40	24.84	53.50	1.18	2.81	15.23	2.72	
Osmium		21.72	43.40		.73	17.39	.69	
Osmium plus iridium	72.89			1.23				2.29
Ruthenium			.50		.54	6.76	2.61	
Rhodium		8.69	2.60	1.12	.85		1.42	1.09
Palladium				.67	1.05		1.39	.77
Iron	5.08							
Copper	.35							
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

1-3. Deville and Debray (1859). Platinum in black sands of the Pacific Coast of California.
4. Kromayer (1862). Platinum from California (black sands).
5. Weil (1859, p. 262). Platinum ores from California.
6. Mean of analyses 1-5.
7. Mean of analyses 1-5, recomputed free of iron and copper.
8. Deville and Debray (1859). Native platinum from a placer deposit at China Flat, Humbolt County.
9. Mean of 11 analyses of the platinum metals of Trinity County, given to the writer by C. C. Stearnes, a mining operator in that County. (Analyses by Wildberg Bros. Smelting and Refining Co. of San Francisco.)
10. Mean of 2 analyses. Deville and Debray (1859). Native platinum from the Trinity River.
11. Cosumnes River, Sacramento County. Collected by writer.
12. Deville and Debray (1859). Locality unknown.
13. Lindgren (1919, p. 790). Analysis quoted from Deville and Debray.
14. Merced River, Merced County. Collected by writer.
15. Trinity County. Collected by writer.
16. Average of 2 analyses from unknown sites in California. J. Bishop and Co. (1931 p. 22).
17. Miscellaneous analysis, county not known.

TABLE 41.—*Incomplete analyses, in percent, of California placer platinum metals*

[Analyses from Logan (1919, p. 109) recomputed to total 100 percent]

	County	Pt	Ir	Os plus Ir
18	Butte	76.91	23.09	
19	Calaveras	65.32		34.68
20	Del Norte	8.8-12.1		50.6-91.2
21	Humboldt	26.13		73.87
22	do	26.92		73.08
23	Mendocino	10.43	51.97	37.60
24	Merced	97.70		2.30
25	Placer	63.87	36.13	
26	do	74.15	25.85	
27	do	71.09	28.91	
28	do	67.33	32.67	
29	do	62.25	37.75	
30	do	51.74	48.26	
31	do	35.37	20.05	44.58
32	Shasta	34.1-82.9		20.4-6.59
33	Siskiyou	2.95		97.05
34	Tehama	13.8-20.5		81.0-86.2
35	Trinity	47.63		52.37
36	do	41.28		58.72
37	Yuba	80.84		19.16
38	do	78.89		21.11
39	do	81.77		18.23
40	do	81.78		18.22
41	do	80.83		19.17
42	do	80.12		19.88
43	do	80.42		19.66
44	do	79.76		20.24
45	do	80.31		19.69
46	do	77.74		22.26

the samples. The first five samples of table 40 show that even in a single county, here it is Humboldt County, the tenor of platinum, recomputed free of iron and copper, ranges from 96 to 63 percent, whereas the tenors in iridium plus osmium, similarly recomputed free of iron and copper, range from 34 to 2 percent. But in table 41 the mean tenors of platinum and iridium plus osmium for samples 21 and 22, also from Humboldt County, are respectively 27 and 73 percent. Hence, the overall ranges in platinum and iridium plus osmium for Humboldt County are respectively 96 to 27 percent and 73 to 2 percent. Over the whole California field, however, the maximum and minium tenors for platinum range from 98 to 3 percent and of iridium plus osmium from 90 to 2 percent. These values indicate the presence of two alloys, one consisting mainly of platinum and the other of osmiridium, generally mixed or intergrown in unknown proportions. A number of analyses, however, indicate the presence of one of these alloys mixed with little or none of the other. Thus, samples 1, 13, 14, 16, 17, and 24 apparently represent alloys with little or no intergrown or intermixed osmiridium. Analysis 9 appears to represent osmiridium mixed with a minor amount of ordinary platinum.

Analyses 12 and 33 represent osmiridium, from which the analyst recovered little or none of the ruthenium, which should be present.

The second characteristic of many of these analyses is the high tenor of iridium plus osmium, which indicates that where the two alloys are mixed or intergrown, osmiridium is an important component. Analysis 9, which represents 11 individual analyses and contains about 59 percent iridium plus osmium, illustrates this feature, as do also analyses 8, 10, 12 (table 40) and 35 and 36 also from Trinity County (table 41). The inference may therefore be drawn that osmiridium is notably prevalent in Trinity County. The same inference, however, also applies to Del Norte, Humboldt, Siskiyou, and Tehama Counties, of the Klamath district. The lowest tenors in iridium plus osmium appear to be prevalent in Butte and Yuba counties, of the piedmont district, but even in these two counties, osmiridium is an important component.

COLORADO

The La Plata mining district is in La Plata and Montezuma Counties, in southwestern Colorado; the Copper Hill mine, with which this discussion is principally concerned, is about one-half a mile northwest of La Plata, in La Plata County. This district was described by Eckel and others (1949). The part of that report which deals with the platinum metals was written by G. M. Schwartz, D. J. Varnes, and E. B. Eckel.

The ore deposits of this district are classified mineralogically into five types, of which one is described as disseminated chalcopyrite with platinum and palladium. This type is exemplified by the Copper Hill mine, which apparently is a contact metamorphic deposit, in which Permian sediments were mineralized and replaced by silicates and ore minerals that originated in a bounding body of syenite. The principal ore minerals are chalcopyrite, hematite, magnetite, and pyrite, which are localized in closely spaced veinlets. Ore taken from the glory hole had a mean tenor of 4.79 percent copper, at least 17 ounces silver to the ton, and small amounts of gold and platinum metals. A tunnel driven directly under the glory hole showed no workable ore, and the rock bounding the glory hole is of distinctly lower grade. The mode of occurrence of the platinum metals was not established, though their tenors increased with that of the copper. Probably the platinum and palladium occurred as minute mineral intergrowths in the chalcopyrite. No assays are available of the platinum metals found in the glory hole, but adjacent to this 80-foot excavation, the tenor of platinum metals was determined to be 0.005 ounce per ton. This deposit is obviously of no importance as a source of platinum metals.

IDAHO

Deposits of extremely fine grained gold and platinum occur along the Snake River across the entire southern part of Idaho, and along the west side of the State where Snake River forms the boundary between Idaho and Oregon. These deposits are to be classed as flour gold and platinum. They have been mined along the river bars and on benches, but most of this work was not profitable. The smallest grains have an average value of about 1 cent for 2,500 grains, but the value may be as low as 1 cent for 35,000 grains. Platinum metals are present but do not attain either the maximum or minimum sizes of the grains of gold. The ratio of gold to platinum is reported by Hite (1933) to be about 2,500:1. Most of the attempted mining was done upstream from the canyon of Snake River, but none of it was important.

MONTANA

STILLWATER COMPLEX

The Stillwater Complex is an elongate assemblage of intrusive rocks that occurs in Sweetwater County, Mont., and extends into Park and Stillwater Counties. It is drained by the Stillwater and Boulder Rivers, which flow northeastward to the Yellowstone River, and its center lies approximately at lat 44°25′ N. and long 110° W. This layered igneous massif, which is classed by Hess (1960, p. 3) as a lopolith, has a length of about 28 miles, a maximum width of 5 miles, and trends N. 70° W., dipping about 55° northward.

The country rock of this area is an uplifted mass of schist and gneiss, intruded by peridotite, anorthosite, norite, and gabbro, which occur in dikes, sills, and bodies of irregular shape and constitute the Stillwater Complex. The schist, gneiss, and most of the intrusives are of Precambrian age, though some intrusives of Cretaceous or Tertiary age have also been recognized. The basic and ultrabasic intrusives are overlain unconformably on the north by folded sedimentary rocks of Paleozoic age; and windows of the crystalline rocks are visible within the sedimentary sequence.

The Stillwater Complex was divided by Howland, Peoples, and Sampson (1936) into four principal zones, as follows:

1. Upper zone, thickness 3,500 feet. This consists of anorthosite, anorthositic gabbro, and anorthositic norite.

2. Banded zone, thickness 5,000 feet. This consists of norite, gabbro, and anorthositic norite, with a band of troctolite near the top, and narrow bands of anorthosite in the basal horizons. At least two bands containing platiniferous sulfides are present.
3. Ultrabasic zone, thickness of 2,500 feet. This consists mainly of bronzitite, harzburgite with chromitic bands, and subordinately dunite, commonly serpentinized.
4. Basal zone, a thickness 300 feet. This consists mainly of diabasic norite.

Later these rocks were subdivided by Hess (1960, p. 50) into 10 zones, of which only the ultrabasic and basal zones correspond with those of Howland, Peoples, and Sampson. Hess also added 4,890 feet to the section and inferred that another 10,600 feet of these rocks have either been eroded or are concealed below the superjacent Paleozoic beds. Later, Jackson (1961) subdivided the ultrabasic zone into two units, consisting of an upper or bronzitite member underlain by a lower or peridotite member. For the purpose of this description, the four divisions of Howland, Peoples, and Sampson, including the two members of the ultrabasic zone, are most useful.

Platinum-bearing minerals have the greatest interest in the Stillwater Complex. Such deposits are stated by Howland, Peoples, and Sampson (1936, p. 10–11) to be of three types. Platinum and palladium have been identified by chemical analyses in the banded zone; chromite deposits occur in the ultrabasic zone; and nickel-copper minerals with small amounts of the platinum elements are present at the basal contact of the complex. The minerals chalcopyrite, pentlandite, and pyrrhotite, which are present in the banded and basal zones, are interstitial to the silicate minerals that form the bulk of these rocks and partly replace some of them. Most, if not all, the platinum metals are believed to occur as platinum minerals that are included as minute crystals in the sulfides of iron, copper, and nickel. The only one of these minerals that has been definitely identified was stibiopalladinite, though sperrylite is probably also present. Native platinum alloys have not been recognized.

Recently, Page and Jackson (1967) have studied the ultrabasic zone and have found at certain of its chromitite horizons a number of sulfides, arsenides, antimonides, and possibly selenides that contain iron, copper, nickel, cobalt, molybdenum, and tin, some of which may be platinum bearing. Platinum-group minerals have also been identified, either in grains of chromite or interspersed with the silicate minerals of the chromitites. One of these is laurite, but others have been recognized that appear to correlate with some of those described by Stumpfl (1961), as mentioned on page 13 of this report.

Concentrations of nickel-copper minerals were found by Howland, Peoples, and Sampson at three principal horizons, of which two were in the banded zone, and one was at the lower contact of the basal zone. Six samples were submitted to the U.S. Geological Survey for analysis, including one from the ultrabasic zone. Four of these were found to contain small amounts of platinum and palladium, with traces of iridium, ruthenium, and rhodium. Osmium was not identified. The localities of these samples, and the results of their assays, are given in table 42.

TABLE 42.—*Analyses of rocks in ounces per ton, from the Stillwater Complex, Montana*

[Analysts, S. H. Cress and K. J. Murata, U.S. Geological Survey]

	MB-215	EB-308	NP-2	MB-236	G-13	H-5-37
Platinum	0.006	--	0.1	0.004	--	0.007
Iridium	--	--	Tr.	--	--	--
Ruthenium	--	--	Tr.	--	--	--
Rhodium	--	--	Tr.	--	--	--
Palladium	.001	--	.2	.007	--	.01

MB-215. McHugh's prospect, east side of valley of Boulder Creek, and 1 mile south of the Boulder Ranger station, at an altitude of 6,000 ft. Sweetgrass County. Anorthosite with disseminated chalcopyrite, pyrrhotite, and pentlandite. Sample from banded zone.
EB-308. West side of Canyon of Lewis Creek, East Boulder plateau, Sweetgrass County. Anorthosite with 15 to 20 ft patches of disseminated pyrrhotite, chalcopyrite, and pentlandite in a 300-ft zone of same material. Sample from banded zone.
NP-2. Near head of North Fork of Picket Pin Creek, Sweetgrass County. Anorthosite with 10-ft patches of disseminated pyrrhotite, chalcopyrite, and pentlandite in a 50-ft zone of same material. Sample from banded zone, and thought to represent the same igneous horizon as samples MB-215, EB-308, and NP-2.
MB-236. East side of valley of Boulder Creek, about 3 miles south of the Boulder Ranger station, Sweetgrass County. From band of norite with disseminated pyrrhotite, chalcopyrite, and pentlandite. Sample from banded zone, but thought to represent a lower horizon than the three preceding samples.
G-13. South side Blakely Creek, tributary Boulder River, Sweetgrass County. Dunite with disseminated chromite. Ultrabasic zone.
H-5-37. Mouat-Sampson mine, 235-ft drift, No. 2 level, "G" layer. West side of valley of the Stillwater River, Stillwater County. Sample taken at lower contact of the basal zone, from sulfide ore that transects a layer of chromite.

Two analyses of rocks from the Stillwater Complex, Montana, made by the International Nickel Co. of Canada, Ltd., (Howland and others, 1936, p. 11) are given in the following tabulation:

	Upper horizon, banded zone	*Mouat mine, below base of the complex*
Platinum, including iridium, ruthenium, and rhodium, not in excess of 1 percent of platinum metals present ounces per ton	0.0725	0.0085
Palladium ounces per ton	.0725	.0025

The methods used in selecting the samples that have been assayed are not known to the writer. If, however, these assays were made on samples of crude broken rocks, even if they were finely crushed and properly parted, the results may not be too dependable. The only proper method for sampling such low-grade ores is to crush and mill them and thereafter to con-

centrate the sulfides or other ore-bearing minerals by the use of a gold pan, or a Wilfley table. Much better assays can be obtained on such enriched samples, and better average values will result. The degree of concentration prior to chemical analysis is readily determinable.

Another phase of this problem must also be stressed. Many assayers who are capable of making high-grade analyses of gold, silver, and the base metals are either too inexpert or unwilling to make high-grade analyses of the platinum metals. This is due in part to the fact that some of the better methods have not been published, but may also result because such analyses are time consuming and costly. The processors of the platinum metals and the Bureau of Standards are perhaps the most reliable sources for such analytical work.

The Stillwater Complex, owing to the occurrence within it of ultrabasic rocks and zones of chromitite, appears to be more closely related to the Bushveld igneous complex of the Transvaal than to the elongate "norite" irruptive of the Sudbury district. In one respect only is there a simulative relationship with the latter. Significant deposits of platiniferous nickel-copper ores are not generally present within the "norite" irruptive, but occur instead either as marginal or offset ore bodies. The Mouat-Sampson mine, of Stillwater County, which is at the lower contact of the basal zone and is associated with noritic rocks is the only property in this area that has been developed. Moreover, according to Howland and others (1936), the Stillwater Complex, for over half its length, is in contact with an iron-stained quartzite of Precambrian age, with a thickness of 200 feet, that is analagous to the Mississagi quartzite of the Sudbury district. Finally, quartz monzonite intrudes both this quartzite and the basal zone of the Stillwater Complex. This similarity, which may in fact be quite fortuitous, is nevertheless a reason for further prospecting along or near the lower contact of the basal zone.

GREEN MOUNTAIN COPPER MINE

Another property in Montana where platinum has been found is the Green Mountain copper mine, in the Revais Creek district, near Dixon, Sanders County. The ore occurs mainly in a vein about 5 feet thick, which follows a fault contact between a gabbro and a quartzite, of the Belt Series. The principal ore minerals are chrysocolla and malachite, and the mine was operated for its content of copper, with a byproduct of gold, silver, and platinum metals. About 5,000 tons of ore was mined intermittently at this property between 1910 and 1942, but the returns were such that the operation was not profitable. Smelter returns between 1938 and 1942 indicated a tenor of about 0.08 ounce of platinum and palladium to the ton of ore. The sources of these platinum metals were not determined, but probably they occurred originally as platinum minerals in unoxidized sulfide ores at greater depth. At least 300 ounces of platinum metals was produced during the lifetime of this mine.

PLACERS

Placer platinum has been reported from several localities in Montana. One of these, with which the writer is personally familiar, comprised the several terraces along both sides of the Missouri River, in Lewis and Clark County, downstream from the Canyon Ferry dam (Mertie, Fischer and Hobbs, 1951, p. 80). The gravels on these terraces were mined for their contents of gold, and at Eldorado Bar, on the north side of the river and 7¾ miles northwest of Canyon Ferry, a dredge was operated from 1938 to 1944. At this site, it was estimated that 8.84 troy ounces of platinum of platinum metals was recovered per 100 pounds of well-cleaned placer concentrates. The platinum from these concentrates was analyzed by the Wildberg Smelting and Refining Co., of San Francisco, and the resulting analysis is platinum 88.91 percent, iridium plus osmium 6.34 percent, palladium 4.75 percent, rhodium not determined, ruthenium not recognized, total 100.00 percent.

NEVADA

The Boss mine is in the Yellow Pine mining district, of Clark County, Nev. This ore deposit was discovered about 1886 and was worked intermittently for copper and gold for 28 years. Platinum was discovered in 1914, and thereafter the mine was worked until 1919. The Boss deposit was an ore shoot of ellipsoidal shape which followed the hanging wall of a fault zone in thick-bedded limestone of Mississippian age. The deposit is not cut by granitic rocks, but a granitic dike appears about 1,500 feet northeast of the mine.

The ore body, from the available descriptions, appears to have been an ellipsoidal ore shoot with a length of about 200 feet and a maximum width of about 25 feet; smaller bodies are also recorded. The ore minerals consisted of dark cellular masses of quartz that contained chrysocolla, limonite, and local concentrations of chalcopyrite, bornite, chalcocite, malachite, and cuprite. Within the ore body were stratified masses and narrow veins of plumbojarosite which was determined by earlier observers to be the source of the precious metals. A sample of this talclike material, collected by Adolph Knopf (1915, p. 878), was analyzed by F. C. Wells, of the U.S. Geological Survey; but the material was

afterwards determined by W. T. Schaller, of the U.S. Geological Survey, to have been a mixture of plumbojarosite, beaverite, and bismutite. Hence, the analysis is of value mainly for the tenors of platinum and palladium that were determined. The stated values show that for such picked ore the tenors of platinum and palladium per ton of ore were respectively 14.6 and 64.2 troy ounces.

The tenors of the platinum ore and crude ore that was mined, however, are much smaller. One assay by Hale (1914) and two other sets of data published by Hewett (1931) bear upon this question. From Hewett's data, one can obtain the weighted mean values of the smelter returns on the "platinum ore" for 1916-19, and the weighted mean tenors of the crude ore for 1917-19. These three values are given herewith:

Hale: 0.5 to 1.0 ounce platinum per ton of ore.
Hewett: 0.32 ounce platinum and 1.10 ounces palladium per ton of "platinum ore."
Hewett: 0.05 ounce platinum and 0.11 ounce palladium per ton of crude ore, or 0.16 ounce platinum metals per ton.

The ratio of platinum to palladium, as gaged by the analysis made by the U.S. Geological Survey, was 1:4.4. The same ratio as gaged by Hewett's smelter returns was 1:3.5.

The mode of occurrence of the platinum and palladium in the plumbojarosite has not been determined. It was suggested by Knopf (1915a, p. 8) that the mineral sperrylite might be present, but this idea was properly rejected by Hewett. Moreover, the platinum-palladium ratio of approximately 1:4 does not fit with this interpretation. From what is now known of the numerous platinum minerals as earlier stated in this report, it is probable that the platinum and palladium exist as separate minerals in the sulfides or other metallic minerals of the ore.

The Boss mine is frequently cited as an unusual occurrence of the platinum metals in a quartz vein. This deposit, however, is not unique in this respect, as the same or similar associations have been recorded at many other places in the world. Among the better known of these are the following:

1. Gold Hill mine, of the Gold Hill quadrangle, Oregon.
2. Quartz veins in West Point mining district, Calaveras County, Calif.
3. Gold quartz vein at property of Roll Call Mining Co., near Villa Grove, Calif.
4. Quartz vein near Boyerstown, Pa.
5. Gold quartz vein at Mother Lode claim, Burnt Basin, 3 miles west of Coryell, Yale district, British Columbia.
6. Quartz vein in granodiorite in Ainsworth mining district, British Columbia.
7. Gold quartz vein in Union Mine, Grand Forks division, British Columbia.
8. Gold quartz vein at mine of Northern Manitoba and Development Co., near The Pas, Manitoba.
9. Quinn claims near the Croesus mine, Munro Township, Ontario.
10. Gold quartz veins in Halifax County Nova Scotia.
11. Guadalcanal, a few miles northeast of Rio Tinto district, Spain.
12. Near Chatelard, Vallee du Drac, Haute Alpes, France.
13. Quartz veins in Thames gold field, North Island, New Zealand.
14. Quartz veins of Hauraki district, North Island, New Zealand.
15. Massive pyrite at Coromandel, North Island, New Zealand.
16. Quartz veins in ultrabasic rocks, North Westland, South Island, New Zealand.
17. Quartz veins associated with serpentine, Teremakau River, South Island, New Zealand.
18. Quartz veins in Lucknow and Alma auriferous reefs, at Gympie, New South Wales.
19. Boa Esperanca veins, Minas Gerais, Brazil.
20. Santa Rosa, north of Medellín, Antioquia, Colombia.
21. Quartz veins of the Waterberg district, Republic of South Africa.
22. Platinum-bearing gold quartz veins of Beresovsk district, Ural Mountains.
23. Quartz veins of northern Finland.

None of these deposits, however, is an important source rock of the platinum metals. They show merely that the platinum metals are not restricted to ultrabasic and basic rocks.

The authenticity of some of the occurrences quoted above may be questioned, particularly at sites where native platinum alloys have been found. It is well known to placer miners that the precious metals at the base of many placers have penetrated downward for 10 to 20 feet into shattered bedrock. If it should happen that the bedrock below a placer consisted of vein quartz, which is brittle and readily shattered, native gold and platinum could readily penetrate into such rock and form an ore body that simulated a gold-platinum lode. The fact that such a lode is far removed from any present stream is immaterial, as alluvial deposits have existed and have been eroded from many

sites. Any gold-platinum lode wherein the precious metals are confined to the uppermost part of the vein is therefore subject to suspicion. In any event, this contingency needs to be disproven before acceptance of all the cited quartz veins as carriers of platinum metals.

Two other prospects in Nevada merit mention. These, known as the Key West and Great Eastern prospects, are in the Copper King mining district, about 25 miles east of Moapa, and about 100 miles northeast of the Boss mine. They were described by Bancroft (1910) as a group of peridotite dikes that consist mainly of augite, olivine, and enstatite, with the accessory minerals pyrrhotite (thought to be nickelferous), chalcopyrite, and magnetite. A shipment of 45.8 tons of ore from the Key West prospect showed tenors of 0.13 to 0.15 ounce of platinum metals to the ton. No recent work has been done.

OREGON

The platinum metals found on the beaches of Oregon and California appear to have originated in bodies of peridotite and serpentinite. The great dike of serpentinite that crops out in the valley of the Applegate River, a north-flowing tributary of the Rogue River, and continues northward may be such a source rock. Platinum was located in the Highland mine, about 12 miles south of Gold Hill, in the Gold Hill quadrangle, Oregon. According to Kellogg (1922, p. 1000), this metal was finally traced to a bluish quartz that was taken from the 100-foot level of the Gold Hill mine. The tenor in platinum, as given by smelter returns, was 0.32 ounce per ton of ore. Serpentinite, however, is probably the major source.

PLACERS

Platinum-bearing gold placers have been found and mined at three localities in Oregon. The most important of these was the Takilma-Waldo district, in Josephine County, about a mile northeast of Waldo and about 30 miles southwest of Grants Pass. Gold was discovered in 1953 on Althouse Creek and thereafter was mined for many years, particularly before 1917 but also up to 1930. A second but less important site was on Applegate River, about 25 miles northeast of Waldo. The third locality consisted of the Pacific beaches of Curry and Coos Counties, which were discovered in 1852 and were worked intermittently for many years. According to Shenon (1933, p. 179), the minimum production of the platinum-bearing gold placers of the Takilma-Waldo district up to 1930 was $4 million, but no estimate is available for Applegate River and its tributaries. No record was kept of the early production of gold and platinum from the ocean beaches of Oregon, but according to Pardee (1934, p. 26), quoting from the U.S. Bureau of Mines, the production of gold between 1903 and 1929 was about $60,000, of which about $2,000 was platinum.

The production of platinum from Oregon in the period 1880–1903, with 9 years not recorded, is given by Quiring (1962, p. 254) as 675 troy ounces, with a maximum output in 1895 of about 130 ounces. Using a gold-platinum ratio of 100:1 for the Takilma-Waldo district, and rating platinum at twice the value of gold at that time, this district may have produced about 1,000 ounces.An unknown part of this output should be added to that given by Quiring for the period 1880–1903, so that the production of platinum metals from Oregon may have been as much as 1,500 ounces.

TAKILMA-WALDO DISTRICT

The deposits of the Takilma-Waldo district include both Tertiary and Quaternary placers. The Tertiary placers, which are in Tertiary conglomerate, are composed of large, greatly altered, boulders of greenstone, granite, argillite, and other rocks in a well-indurated sandy matrix. Gold and platinum are distributed throughout the conglomerate and are only slightly concentrated near bedrock, which suggests local sources. Well-known deposits in the Tertiary conglomerate that were worked at a profit were the High Gravel, Cameron, and Platerica mines. The ratio of gold to platinum is reported to have ranged from 75:1 to 100:1, but no assays or analyses of the platinum appear to have been made. The principal heavy and semiheavy minerals recovered with the precious metals were chromite, magnetite, limonite, hematite, ilmenite, epidote, and zircon.

The more valuable deposits of the Takilma-Waldo district were gravel deposits on terraces or in the present valley floors One of the best known properties of this group was the Logan mine, later known as the Llano de Oro mine, but best known perhaps as French Flat. This was a terrace from 15 to 20 feet high, on the west side of the East Fork of the Illinois River, about a mile northeast of Waldo. The deposit consisted of imperfectly sorted gravel, sand, and clay ranging in thickness from a foot at its outer edge up to 50 feet. The gold was angular and was associated with chromite, magnetite, ilmenite, hematite, limonite, epidote, and zircon. The ratio of gold to platinum was reported to have been about 50:1. According to Shenon (1933, p. 187), a sample of the platinum was analyzed by E. T. Erickson, of the U.S. Geological Survey, who reported that it consisted largely of platinum and ruthenium, less iridium and osmium, and very small amounts of palladium and rhodium. This

analysis differs from any other known to the writer, and if reliable, is indeed unique.

Other deposits worked in the Takilma-Waldo district were the Deep Gravel mine, and those on Fry, Waldo, Allen, Butcher, and Sailor Gulches. These properties were mainly in the vally floors of the present streams and were concentrated from the Tertiary conglomerate, which constituted a proximate source rock. Platinum was undoubtedly recovered from these deposits, but its presence was not mentioned either by Hornor (1918) or by Shenon (1933).

APPLEGATE DISTRICT

Applegate River is a northwest-flowing tributary of Rogue River. Mining was carried on in the Applegate district for years after mining ceased in the Takilma-Waldo district. A nonfloating dredge, probably mounted on skids and moved by a caterpillar, was operated on the Applegate River in 1944, and two others were operated in the Applegate drainage. In addition, some mining was in progress on Forest and Poorman Creeks, tributaries of the Applegate River. The following analysis of platinum, made by the Wildberg Smelting and Refining Co. of San Francisco, was given to the writer by an operator on the Applegate River: platinum 29.70, iridium 31.96, osmium 25.56, ruthenium 12.78, rhodium not determined, total 100 percent. This is clearly a mixture of osmiridium with ordinary platinum, wherein osmiridum is a major component.

PACIFIC BEACHES

The beach deposits of Oregon have been well described by Pardee (1934). In Curry County the principal localities, named from south to north, were the mouth of Chetco Creek, Ophir Creek, the mouth of Pistol River, Gold Beach at the mouth of the Rogue River, Eucher Creek, Port Orford, and Cape Blanco near the mouth of the Sixes River; in Coos County, Bandon at the mouth of the Coquille River, Old Randolph on South Slough, and Coos Bay at the mouth of Coos River. These deposits were discovered in 1852, and those of higher grade were soon exhausted, yet many of them were worked intermittently for years afterwards.

The coastal ranges of Oregon are bounded on the west by a narrow Pacific coastal plain that ranges in width from a quarter of a mile to 4 miles and in altitude from sea level to 100 feet, with numerous low marine terraces. There are also higher terraces at or about 170 feet above sea level and one higher terrace at an altitude of 800 feet. Deposits at the 170-foot level were worked at two mines east of Cape Blanco and at four mines north of Cut Creek. The Peck mine, at an altitude of 800 feet, was on a spur north of the Sixes River, and still other terraces up to an altitude of 1,500 feet are present, though none of these was mined. The terrace deposits, however, proved not to be as high grade as those in the coastal plain or low terraces. Probably the richest deposits were found south of Coos Bay, but the beaches at Whisky Run, Cape Blanco, Port Orford, and Gold Beach were also remunerative.

The platinum metals and the gold are extremely fine, rounded, flat grains from 0.8 to 0.05 millimeter in diameter and from 0.05 to 0.005 millimeter in thickness, but range downward to grains of microscopic size. The ratio of gold to platinum varied from 100:1 to 160:1. The heavy and semiheavy minerals on the Port Orford and adjacent beaches were found to be mainly magnetite, chromite, ilmenite, garnet, and olivine. Some zircon and monazite were also found at Coos Bay.

Two chemical analyses, which are believed to represent the platinum of the littoral deposits, have been published and are presented in table 43. It may be assumed that most of the "osmium plus iridium" recorded in table 43 is iridium, but these analyses, owing to the high percentage of platinum, do not represent osmiridium alone. On the other hand, the high tenors in osmium plus iridium indicate that much osmiridium is present. If these analyses represent an alluvial mixture of two alloys, as may well be true, they suggest that the ratio of osmiridium to platinum is high. Owing to the low percentage of rhodium, these two analyses do not correspond closely with any of those recorded for California.

TABLE 43.—*Analyses, in percent, of platinum metals from Pacific beaches of Oregon*

[N.D., no data]

	A	B
Platinum	53.37	57.20
Iridium	.42	.45
Osmium	N.D.	N.D.
Osmium plus iridium	38.69	41.46
Ruthenium	N.D.	N.D.
Rhodium	.67	.72
Palladium	.16	.17
Iron	4.46	N.D.
Copper	2.23	N.D.
Total	100.00	100.00

A. Deville and Debray (1859); republished by Kemp (1902, p. 19).
B. Deville and Debray (1859).

Platinum metals have been found, generally as traces, in many other counties of Oregon, and from Baker County there was a small production in 1925. Platinum has been identified in Jackson, Douglas, Lincoln, Linn, Clatsop, Washington, and Multnomah

Counties, in the western part of the State; Wheeler and Grant Counties, in the central part; and Union County, north of Baker County, in the eastern part of the State.

WASHINGTON

Gold was found along the beaches of Washington about 1894, and the ground was staked for 60 to 70 miles south of Cape Flattery, Clallam County; but the productive strip was later determined to be from Portage Head, about 8 miles south of Cape Flattery to Cape Johnson, just north of Quillayute River. The most productive locality was at Shi Shi Beach, near Portage Head, where at least $15,000 in gold was recovered prior to 1904. The total production of gold probably did not exceed 1,500 troy ounces. The material from which the gold was concentrated, however, was of glacial origin, and the ratio of gold to platinum was estimated to have been from 15:1 to 5:1. Therefore, although the platinum was probably overlooked, some 150 ounces of platinum may have been handled in these operations. It was later determined that the grains of platinum were only about one-fourth as large as those of the gold and that about 10 percent of them were ferromagnetic.

Gold and platinum were also produced on a small scale along a short stretch of the South Fork of Lewis River, a short distance above Moulton, in Clark County. A few ounces of platinum metals are reported to have been produced. Traces of platinum metals have also been found in Pacific, Lewis, Thurston, King, Skagit, and Whatcom Counties, in western Washington; in Okanogan County, in north-central Washington; and in Garfield County, in southeastern Washington.

WYOMING

The Rambler mine and nearby Centennial mine merit brief mention. The Rambler mine is in the Medicine Bow Mountains, about 10 miles north of the Colorado line and about 45 miles west of Laramie City. This is an ore deposit of irregular shape, which occurred in a dike or small stock of dark-colored greatly decomposed diorite, bounded by quartzite. The Centennial mine was in gneiss and schist. The ore minerals of the Rambler mine were covellite, chalcopyrite, pyrite, cuprite, azurite, malachite, and kaolin. The feature of greatest interest was the recogniton of extremely minute crystals of sperrylite intergrown with the covellite. The source of the palladium contained in the ore was not ascertained. According to Taft (1918, p. 900), the tenors of platinum and palladium in the ore were respectively 0.6 and 0.4 ounce per ton of ore; and another assay from an independent source showed a total of 1.3 ounces of platinum metals to the ton of ore. According to Paul Theobald of the U.S. Geological Survey (written commun., 1967), preliminary analyses of samples from the mine dump show from 0.2 to 20 parts per million (0.006–0.6 ounce per ton) of platinum metals, and check analyses of five samples showed 2.1 to 4 parts per million. The ratio of palladium to platinum is about 5:1. The Rambler mine was a small deposit which was quickly exhausted.

RECOVERIES FROM REFINERIES

Platinum metals are recovered in the mining of gold and copper from refineries where these two metals are purified, and also from secondary sources. The amount obtained from copper ores may properly be classified as a product of lode mining, whereas that recovered from gold ores and bullion is an increment gained both from lode and placer mining. The platinum metals from the placer deposit at Goodnews Bay, Alaska, together with any such metals that originate as a byproduct of other gold placer mining, are combined with those derived from all primary domestic sources to arrive at the output of 35,026 troy ounces cited in table 2 as the production for 1965. In addition, there was an output of 106,525 ounces obtained from domestic secondary sources. Hence, more than a million ounces of platinum metals had to be imported to satisfy the industrial needs of the United States for 1965.

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An older bibliography of 150 titles on iridium, for the period 1803–85, deserves mention. This was prepared by A. N. Perry and appeared in the U.S. Geological Survey Mineral Resources volume for 1883–84.

A third bibliography of the physical properties of the platinum metals and their alloys by Douglass and Jaffee(1960), is also very useful.

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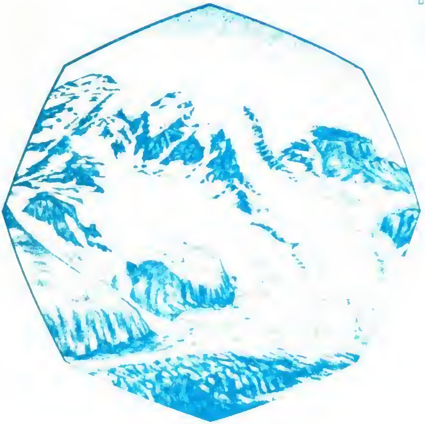
ANALYSIS OF A 24-YEAR PHOTOGRAPHIC RECORD OF NISQUALLY GLACIER

MOUNT RAINIER NATIONAL PARK WASHINGTON



Geological Survey Professional Paper 631

Analysis of a 24-Year Photographic Record of Nisqually Glacier, Mount Rainier National Park, Washington

By FRED M. VEATCH

GEOLOGICAL SURVEY PROFESSIONAL PAPER 631

A contribution to the
International Hydrological Decade

UNITED STATES DEPARTMENT OF THE INTERIOR

WALTER J. HICKEL, Secretary

GEOLOGICAL SURVEY

William T. Pecora, Director

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ANALYSIS OF A 24-YEAR PHOTOGRAPHIC RECORD OF NISQUALLY GLACIER, MOUNT RAINIER NATIONAL PARK, WASHINGTON

By Fred M. Veatch

Abstract

A systematic coverage of Nisqually Glacier by photographs taken from a network of stations on the ground was begun in 1942 to explore the value and limitations of such photographs as an aid in glacier study. Principles developed may be of value elsewhere, especially for the program "Measurement of Glacier Variations on a World-Wide Basis" of the International Hydrological Decade.

Nisqually Glacier in Mount Rainier National Park, Wash., covers 2.5 square miles (6.5 square kilometers) (1961) and extends from an altitude of about 14,300 feet (4,400 meters) near the top of Mount Rainier down to 4,700 feet (1,400 meters), in a horizontal distance of 4.1 miles (6.6 kilometers).

Analyses were made of the annual photographs taken by the writer for 24 years from about 20 stations. A number of pictures taken sporadically from 1884 to 1941 by others were also available for use in the study. Where possible, the results obtained from photographs were compared with those from the available engineering surveys. Such detailed analysis of an extensive photographic coverage of a single glacier may be unique.

Photographs illustrating the retreat and advance of the glacier's west ice margin in a reach extending for about a mile (1.6 kilometers) downstream from Wilson Glacier show that, by 1965, most of the ice thickness lost in that area between 1890 and 1944 had been recovered. Withering of the stagnant valley tongue down glacier from the nuntak is portrayed, as is its spectacular reactivation in the 1960's by a vigorous advance of fresh ice. Some of the visible characteristics of advancing and receding termini are noted.

Annual values of the glacier's surface slope (5 to 10 degrees) at a cross profile were measured on photographs with respect to a projected vertical line identifiable in each picture. The results were found to average about 2 degrees less than those obtained from the 5-year topographic maps, but they are thought to be a little more accurate owing to lack of a sufficiently small contour interval on the maps for this special purpose.

Year-to-year variations in the surface slope and other characteristics from place to place along the glacier are portrayed by pictures to a degree not economically attainable by any other means.

Annual changes in the glacier's thickness at two locations were determined from photographs and found to agree well with the results of stadia surveys.

A summary of conclusions reached in regard to other data or features of the glacier that were illustrated by annual photographs follows:

1. Toward the end of the ablation season, position of the annual snowline ranged between altitudes of about 5,800 and 7,300 feet (1,750 and 2,250 meters). The altitude limits within which firn was observed on the glacier were about 6,000 and 7,300 feet (1,850 and 2,250 meters).
2. Sources from which debris reaches the glacier are evident.
3. Medial moraines and other persistent patterns sometimes overlooked in the field are more noticeable in photographs. Ice-cored moraines and patterns of multiple lateral moraines are visible.
4. The extent, severity, and nature of crevassing in an area reflect the dynamic condition of the glacier at that location.
5. Erosion has caused certain bedrock areas or features on canyon walls to become unrecognizable within less than 15 years.
6. Effects of the 1932 and 1955 outburst floods on the stream channel and trees for a mile (1.6 kilometers) or so below the glacier are shown in comparison with ordinary, lesser floods. Visible effects include degradation, widening and changes in configuration of the channel, formation of small terraces, removal of vegetation from the flood plain, and the deposition of huge boulders on the stream banks and flood plain.

Some photographic procedures recommended for use in a program of this type are described in the section on "Recommended Photographic Procedures."

INTRODUCTION

PURPOSE AND SCOPE

Reasons for the program

Over the years, glaciers show marked changes. For their study and analysis a repetitive photographic program has obvious potential value because it is relatively quick and inexpensive and can include a wealth of information unobtainable by ordinary surveying techniques. Such a program graphically portrays the

visible characteristics and changes inherent in a fluctuating glacier. Since this has long been recognized, systematic photographic programs have been undertaken on many glaciers in many parts of the world. However, no such program, to the knowledge of the writer, has combined a fairly detailed photographic coverage over nearly the full length of a single glacier, a long period of annual record, and an analysis of the potential of a program such as is described in this paper.

Published reports by Field (1932, 1937, 1947), Harrison (1954, 1956), LaChapelle (1962), Meier and Post (1962), and others have utilized glacier photographs, but the pictures for any one glacier did not include coverage or length of record as detailed as those available for Nisqually Glacier, nor did the reports indicate the many kinds of data obtainable from such photographs. Such an analysis is especially important now because a photographic record has been designated as a first, least costly step, in the new program "Measurements of Glacier Variations on a World-Wide Basis" of the Commission of Snow and Ice (International Association of Scientific Hydrology). This global-scale program is also part of the International Hydrological Decade. Thus, the findings and techniques described herein are thought to have possible application elsewhere.

The idea that worthwhile benefits might derive from a long-term program of annual photographs of Nisqually Glacier was conceived by the writer in collaboration with Arthur Johnson of the U.S. Geological Survey when Mr. Johnson was mapping the glacier in 1941.

Soon after the annual photographic records were begun, a marked thickening of the upper part of the glacier was noticed from the annual cross-profile surveys (Johnson, 1949). The thickening was followed over a period of two decades by one unusually large and several smaller kinematic (moving) waves of fresh ice advance. The effect of these was particularly impressive in the terminal area from 1963 to 1965. The waves probably resulted from the marked increases in precipitation on Mount Rainier as evidenced in the measurements at Paradise Ranger Station, situated less than a mile (1.6 km (kilometers)) from the glacier at an altitude of 5,430 feet (1,160 m (meters)).

The climatic change of the late 1940's, which subsequently was found to have caused the advance of glaciers in many parts of the world, apparently was first detected in 1946 and 1947 in glaciers on Mount Rainier. As a result, Nisqually Glacier became an object of considerable international scientific interest.

A program of this kind is less expensive than one based on aerial or phototheodolite photography because it does not require trained photogrammetrists or as costly equipment. Furthermore, since it consumes relatively little field time its success is more certain during brief periods of cloudless weather.

Purpose of the report

The primary purpose of this report is to describe, and demonstrate by means of examples, what kinds of data usable in analyzing glacier characteristics can be obtained from a simple program of long-term photographic coverage from stations on the ground. It is not intended to be a detailed or complete report on the glacier's physical characteristics.

Secondary purposes of the report are to describe to interested workers the photographs available here and to illustrate some of the spectacular changes that have occurred in this glacier. Examples are given of qualitative and quantitative data sought in regard to the glacier's growth, depletion, movement, slope, moraines, crevassing, snow and firn lines, and debris cover. Some objectives that developed as the photographic program progressed were the illustration of some geomorphological changes occurring in old moraines and the adjacent hills and valley, and the portrayal of erosion and other changes in the river channel below the glacier from outburst floods and other causes.

The report presents photographs taken by the writer for 24 years from about 20 stations and some older photographs taken by others. Only a hand-held amateur camera was used, without photogrammetric instruments of any nature. Office techniques used included the interpretation and marking of ice margins and slope crest lines on photographs, and the performance of simple scaling, scale-ratio computions, and angle measurements.

Selection of study area

Nisqually Glacier on Mount Rainier, Wash., was chosen for the project because of its variety of features for such an experiment, the availability of data from previous investigations, the many concurrent topographical and profile survey data which could be used for checking, the superior accessibility of this glacier, and the practical local interest in it as an important source of the water supply of the Nisqually River. The general location and access to the glacier are shown in figure 1.

Quantities of melt water coming from Nisqually Glacier vary with the amounts of snow and ice it contains and with external conditions such as air temperature and the amount of radiant energy received from the sun. Streamflow records show that the discharge of the Nisqually River is markedly affected by variations in the melting rates of headwater glaciers. Thus, because the river is used for the production of

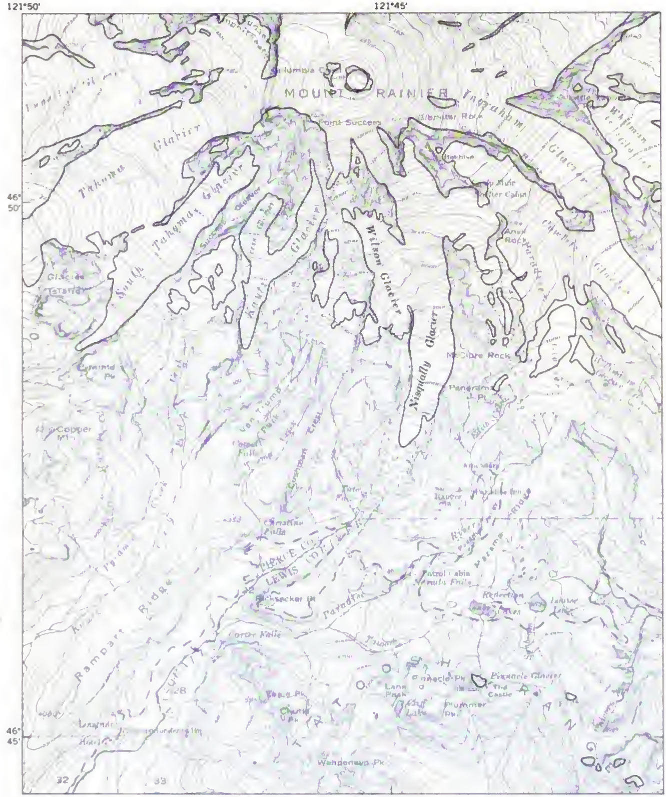

Figure 1.—South side of Mount Rainier and vicinity, showing location of Nisqually Glacier. Glacier margins and part of culture corrected to 1966. Scale 1 inch = 62,500 feet (approximately 1 inch = 1 mile).

power at hydroelectric plants downstream from Mount Rainier National Park, any study of glacier fluctuations and related climatic changes is of important economic interest in connection with the long-range planning of water resource use.

PREVIOUS INVESTIGATIONS

Photographs

Nisqually Glacier in Mount Rainier National Park long has been a favorite object of photographers, for it is a readily accessible subject for glacier research and is part of a high-altitude area of rare scenic grandeur. For many years (until 1936) its terminus remained less than half a mile (0.8 km) upstream from the former highway bridge on the road to Paradise Inn. The main body of Nisqually Glacier is visible from several vista points along its east side, accessible from the Paradise Inn area (pl. 1).

Numerous random photographs, mostly confined to the area of the terminus, were taken in association with surveying activities. The first known photograph of the glacier was a view of the snout taken by Allen C. Mason in 1884.

I. C. Russell (1898, p. 399–400), as a member of a U.S. Geological Survey group making a reconnaissance of Mount Rainier and its glaciers, recommended systematic photographic coverage and measurement of the position of the Nisqually Glacier terminus from permanent, marked locations. Russell also reported that Nisqually Glacier affords abundant opportunity for observation and study of the various features that glaciers possess, such as crevasses and moraines. No network of regularly scheduled photographs covering most of the glacier was established until 1942, nearly half a century later, when a program of annual photographs from about 20 stations was initiated by the writer, then district engineer, Water Resources Division, Geological Survey, Tacoma, Wash.

Surveys and maps

A definite location of the terminus of Nisqually Glacier was recorded first in 1857, by Lt. A. V. Kautz, and next in 1885, by James Longmire. Its approximate position in 1910 was determined on the small-scale planetable map of Mount Rainier National Park that was made in 1910–13 by the U.S. Geological Survey under the supervision of F. E. Matthes. Annual records of the position of the terminus, begun in 1918 by F. W. Shmoe, National Park Service, were obtained each year by that agency until 1961 and have been continued since then by the Conservation Division of the U.S. Geological Survey.

In 1930 and 1931, Llewellyn Evans, superintendent of the Light Division, Tacoma Department of Public Utilities, made cross-profile and other surveys and compared the results with data taken from Matthes' 1910 map. In 1931 a contour map was prepared cooperatively by the Tacoma [City] Light Division, the National Park Service, and the U.S. Geological Survey. A plan of contour mapping at 5-year intervals was then conceived by Llewellyn Evans, Owen A. Tomlinson, and Glenn L. Parker of those respective agencies. This has been done, beginning in 1936, first by planetable and later (covering a larger area) using photogrammetry from aerial photographs, by the U.S. Geological Survey in cooperation with the city of Tacoma and the National Park Service. At the request of the Tacoma Light Division a map of the same type was also made in 1940; it was not published but is on file in the office of the Conservation Division, U.S. Geological Survey, Tacoma, Wash.

Nisqually Glacier was also mapped by terrestrial photogrammetry in 1952 and 1956 by Walther Hofmann of the Technical Institute in Munich, Federal Republic of Germany (Hofmann, 1958).

Beginning in 1940, the Conservation Division of the U.S. Geological Survey, under the supervision of regional hydraulic engineers Arthur Johnson (to 1952), Fred A. Johnson (1953–62), and Gordon C. Giles (1963–), has made annual surveys by stadia techniques of three cross-profiles of the glacier (locations on pl. 1). The Conservation Division also has made surveys of glacier movement and has reported on recession and volume changes (Johnson, 1960). The surveys have been carried out with the assistance and cooperation of National Park Service personnel and, in some years, with the financial assistance of the Tacoma Department of Public Utilities.

The 1956 map used for showing locations of the photographic stations and cross profiles was prepared by the Topographic Division of the U.S. Geological Survey, which obtained the topography from aerial photographs by using a Wild A–8 plotter.

ACKNOWLEDGMENTS

This report was prepared under the general supervision of Mark F. Meier, geologist in charge of glacier research. The assistance of Austin Post and Donald Richardson was very helpful. Collaboration of several colleague reviewers, especially Arthur Johnson and Gordon C. Giles of the U.S. Geological Survey and W. O. Field of the American Geographical Society, is gratefully acknowledged. The Tacoma Department of Public Utilities furnished several photographs and assisted in the preparation of photographic illustrations for the report. Some photographs and the data on changes in ice-surface elevation at the cross profiles were supplied by the Conservation Division of the U.S. Geological

Survey. The cooperation of the National Park Service and the Washington State Historical Society in making their photographic files available is appreciated.

DESCRIPTION OF THE AREA

PHYSIOGRAPHY

Nisqually Glacier extends from an altitude of about 14,350 feet (4,370 m) near the summit of Mount Rainier southward 4.1 miles (6.6 km) to a terminus (in 1966) at an altitude of 4,640 feet (1,410 m) for a total drop in elevation of about 9,700 feet (2,960 m). It is divided by Nisqually Cleaver into two channels from altitudes of 13,100 to 9,500 feet (3,990 to 2,900 m) in a horizontal distance of about 3,200 feet (980 m). Ice flow in the east channel is discontinuous at the steep cliffs opposite the upper part of Cowlitz Cleaver, where the ice stream is discharged in the form of intermittent avalanches or falls. If the glacier thickened sufficiently, the flow at that point would be continuous.

The glacier is fed from the west between altitudes of 8,600 and 7,100 feet (2,620 and 2,160 m) by Wilson Glacier, as shown on the maps in figure 1 and plate 1 and in the photograph in figure 34. Wilson Glacier originates in a shallow cirque and occupies a short, wide basin on the south flank of the mountain. It is fed mainly by snowfall and snow avalanches, but it also receives a minor icefall or avalanche discharge from part of an upper lobe of Kautz Glacier.

Nisqually Glacier has a surface width of approximately half a mile (0.8 km) from the foot of Nisqually Cleaver to profile 2 (pl. 1). Below profile 2 it tapers to a width of 500 feet (152 m) near the terminus. Its total area, including Wilson Glacier, was measured on the 1961 map as about 2.5 square miles (6.5 km²).

The following tabulation augments the description of the glacier by providing basic data on the locations and altitudes of several features, as taken from the 1961 map, including rough approximations of the surface slope for the reaches between those features:

Feature	Distance above old highway bridge		Midglacier altitude in 1961		Slope (degrees)
	Feet	Meters	Feet	Meters	
Terminus in 1961 (crest of face)	5,830	1,780	4,800	1,460	
					25
Profile 1	6,870	2,100	5,290	1,610	
					17
Profile 2	9,390	2,860	6,050	1,840	
					13
Profile 3	12,850	3,920	6,840	2,080	
					16
Base of lower icefall and approximate firn limit [1]	14,460	4,410	7,300	2,220	
					30
Top of upper icefall (near top of Nisqually Cleaver)	24,400	7,440	13,100	3,990	
					27
Head	26,800	8,170	14,350	4,370	

[1] In this report, the term "snow" is restricted to that which fell during the most recent winter season, and "firn" designates granular snow that has survived one or more ablation seasons.

Nearly 8,000 feet (2,440 m) up valley from the site of the former highway bridge and 1,200 feet (370 m) above profile 1, the glacier flows past and sometimes over a nunatak [2] (fig. 27). The top of the nunatak is at an altitude of 5,670 feet (1,730 m). It currently diverts a major part of the east-half ice flow toward the west wall of the canyon; for more than 10 years, from the early 1940's to the mid-1950's, essentially all the ice flow was west of the nunatak.

CLIMATE

The Nisqually Glacier area receives most of its precipitation from moist, eastward-flowing cyclonic storms which form over the Pacific Ocean on the south edge of the winter Aleutian low-pressure area. More than 80 percent of this precipitation falls as snow during the period October to May. Since the low-level winds normally flow from the southwest during these winter storms, Nisqually Glacier, lying as it does on the south side of Mount Rainier, receives nearly the full effect of the storms. A precipitation shadow lies to the northeast of the mountain.

During the period 1920–59 the annual precipitation at Paradise Ranger Station (fig. 1), at an altitude of 5,430 feet (1,660 m), averaged 106 inches (269 mm) for the 24 complete but noncontinuous years of available record. On parts of the glacier, particularly at higher altitudes, the precipitation may have been greater. Snow depths at Paradise sometimes reach 30 feet (9 m). The range in annual precipitation recorded there during the 1920–59 period was from 64 to 138 inches (163 to 351 mm).

THE PHOTOGRAPHIC PROGRAM

NETWORK OF STATIONS

Several of the photographic stations were established at sites from which miscellaneous earlier photographs had been taken—for example, the 1899 view that was published in the 18th Annual Report of the U.S. Geological Survey. Additional stations were selected to improve the overall coverage and to collect some views illustrating geomorphological changes in the hills and valley. The objective was to provide fairly complete coverage of the glacier and valley below, with at least two angles of view available for every area insofar as feasible.

Along the east side of the glacier two "tiers" of stations were used—one as high as feasible and the other

[2] This rock hill was termed a nunatak by Giles (1960), is locally known by this name, and is so termed herein. However, this knob does not always project above the surface of the ice, nor is it always surrounded by ice, so it does not always fit the accepted glaciological definition of "nunatak."

not far above the glacier surface. The higher stations provide most of the information needed for study of the glacier, but the lower ones are especially useful in any analysis of longitudinal surface slope or in any photographic determinations of rates of surface movement (the latter subject was not studied in this report).

The selection of photographic stations, except near the highway bridge, was restricted to the more accessible east side of the glacier. An attempt was made to avoid hazardous areas, such as those too precipitous or subject to rolling rock, and sites where tree growth or rise of the glacier surface might later obstruct the view.

A brief description of each photographic station, including its period of record, is given in table 1; the locations are shown on plate 1. The approximate direction of every panoramic view photographed from each station is indicated on plate 1. Each view series is given a serial number corresponding to the number of the station, with direction of the view added when necessary for differentiation between series. Footnotes explain the changes that have been made in the location of each station.

PHOTOGRAPHIC SERIES NOT PUBLISHED

Several of the photographic series shown on the map and in the description list are not discussed in this report but are included to indicate their availability in the files of the U.S. Geological Survey, Tacoma, Wash., should they later become of interest. These are series Nos. 1–SW, 2–NE, 4, 5–W, 8–W, 8–N, 9, 10, 12, 14–N, 16, 17–S, 17–NW, 18–S, and 18–NW. Some have been discontinued.

TABLE 1.—*Descriptions of the photographic series, 1890–1965*

Series	Figures	Years of record	Altitude: Feet	Altitude: Meters	Geological Survey period of record	Direction of view relative to glacier	Place from which photographs were taken
1–NE	16–19	[1] 20	3, 900	1, 190	1942, 1947, 1949–	Up	Highway bridge on Nisqually River.
1–SW		20	3, 900	1, 190	1942, 1947–	Down	Do.
2–NE		20	4, 300	1, 310	1943–50, 1952, 1953, 1956–	Up	Stone monument on cliff.[2]
2–S	39	17	4, 300	1, 310	1943, 1947–50, 1952, 1953, 1956–	Down	Do.
3	36–38	14	4, 150	1, 260	1941, 1942, 1947, 1952, 1956–	do	Viewpoint ¼ mi (0.4 km) north of Ricksecker Point.
4		10	4, 250	1, 300	1944, 1955, 1958–	Up	Canyon Rim viewpoint.[3]
5	20–25	21	5, 240	1, 600	1940, 1942–45, 1949–52, 1954–	Up	Nisqually Vista, at trailside exhibit.
5–W		[5] 13	5, 240	1, 600	1943–46, 1949–57	Across	Do.[4]
6	27–31	24	5, 560	1, 690	1942–	Up	Point on cliff.[6]
7	2–5	16	5, 760	1, 760	1890, 1940–42, 1945, 1948, 1951, 1954, 1958–	Up	Bend in trail to glacier (1890 station).
8–W		21	5, 580	1, 700	1941–46, 1951–	Across	18 ft (5.5 m) west of B.M. 5587, on old moraine.
8–N		27	5, 580	1, 700	1931, 1936, 1941–	Up	Do.
9		10	6, 040	1, 840	1915, 1943, 1955, 1958–60, 1962–	Across	60 ft (18 m) west of old trail on ridge.[7]
10		19	5, 860	1, 790	1947–	do	Point on moraine trail.
11	35	16	6, 050	1, 840	1940, 1947, 1951–53, 1955–	Down	Do.[8]
12		13	6, 074	1, 850	1936, 1941, 1955–	Across [9]	B.M. 6074, on old moraine.
12–N	26	3	6, 074	1, 850	1940, 1955, 1956	Up	Do.
13	32–34	17	6, 325	1, 930	[10] 1949–	Across and up	Point on bedrock beside Skyline Trail.
14–W	7–10	18	6, 165	1, 880	1942–44, 1951	Across	B.M. 6165, on moraine.
14–N		20	6, 165	1, 880	1942–44, 1947, 1951–	Up	Do.
15	12	22	6, 293	1, 920	1943–46, 1948–	Up	B.M. 6293, on moraine.
16		17	6, 428	1, 960	1949–65	Across and up	B.M. 6428, on moraine.
17–S		2	6, 800	2, 070	1964–	Down	Large rock on a moraine.[11]
17–NW		2	6, 800	2, 070	1964–	Across and up	Do.[11]
18–S		17	6, 882	2, 100	1943–44, 1946, 1948–55, 1958–62, 1964	Down	B.M. 6882, on large imbedded rock.[12]
18–NW		17	6, 882	2, 100	1942–44, 1948–55, 1958–62, 1964	Across and up	Do.[12]

[1] Used old bridge through 1960 and new bridge several hundred feet downstream and a little higher in elevation, 1959–65. Numerous photographs looking up glacier from station 1 are available in the files of other agencies.

[2] Prior to 1964 this series was taken about 100 ft (30 m) farther up glacier, at old survey stake No. 1185.

[3] 1944 taken from road ¼ mile (0.4 km) south; 1955 and 1959 taken from bend in road 0.7 mile (1.1 km) south of Canyon Rim viewpoint.

[4] Prior to 1949 taken from bend in trail about 100 ft (30 m) northeast of Nisqually Vista.

[5] After 1957 the terminus was photographed in series 5.

[6] Prior to 1957 taken from site about 200 ft (60 m) west and 50 ft (15 m) lower in altitude.

[7] 1943 view taken from about 200 ft (60 m) north of 1915 site, and all views thereafter taken from new point about 400 ft (120 m) north of 1915 site.

[8] Taken from 3 points with a radius of 25 ft (8 m).

[9] Usually panoramas covering about 135° down, across, and up glacier.

[10] The 1949 photograph was taken at or near B.M. tablet 4–1940 situated about 500 ft (150 m) up glacier from the bedrock point used thereafter.

[11] This point established to supersede B.M. 6882 to obtain less hazardous access.

[12] In 1943, 1944, 1948, 1951, and 1953 the views were taken from B.M. 6853 which is about 50 ft (15 m) west and 30 ft (9 m) lower than B.M. 6882.

TIME OF YEAR AND WEATHER CONDITIONS

To obtain information on annual accretion, wastage, and movement of ice in Nisqually Glacier, the photographs have been taken as late in the ablation season as thought safe before a heavy, fresh snowfall might occur. Early in the program the photographs were taken in late August, but more recently they have been taken during the first 2 weeks of September. Although the minimum mass of glacier ice and snow normally occurs in late September, photographs are taken earlier to avoid risk of a snowfall which would conceal features such as the firn line.

The climate at Nisqually Glacier is characterized by rapid changes in weather which are difficult to predict owing to the paucity of weather data beyond the coastline. Such changes may seriously interrupt completion of the photography, and they sometimes necessitate a second trip to Mount Rainier. Weather variations make it much more difficult to schedule aerial photography or to spend a number of days in cumbersome (though more precise) phototheodolite procedure; this emphasizes the economy of using a hand camera in one quick trip that can take full advantage of a brief break in the weather.

CAMERA EQUIPMENT

Cameras used for taking the 1942–65 pictures mentioned in this report were: 1942–57—Kodak Model 3–A, film size 3¼ by 5½ inches, focal length 170 mm, equipped with cable shutter release: 1958–65—Kodak Tourist, film size 2¼ by 3¼ inches, focal length 105 mm. Exposures normally were for 1/200th second at f–11 or f–16, and were all made with the camera handheld.

In general, Kodak Super XX film (speed ASA 100) was used from 1942 to 1955 and Kodak Verichrome Pan (ASA 80) thereafter. The relatively low graininess of these films and their latitude to accommodate the contrasting lighting encountered in glacier scenes have been satisfactory.

In this program, the experimental use of lens filters, particularly the K–2 (yellow) one, have shown no advantage over the unfiltered lens.

LIGHT CONDITIONS

An effort was made to take the annual view at each station at the same hour of the day, as well as at the same time of year, so that similar light conditions would minimize illusory effects and possible misinterpretations. This was not always feasible, but analyses made during preparation of this report emphasize the importance of following such a procedure.

SCALE CORRECTIONS ON PRINTS

The selected enlargements or prints in each photographic series utilized in the quantitative analyses in this report were reduced to the same scale by developing and applying scale-ratio coefficients. These were obtained by scaling the linear distances between identical fixed points (features in bedrock) common to all the prints, and determining the ratio between the value for each print with respect to the comparable value on a selected base print. The resulting coefficients were applied to any analytical data measured on those prints to reduce all measurements to the scale of the base print.

QUANTITATIVE INTERPRETATIONS FROM THE PHOTOGRAPHS

CHANGES IN ICE THICKNESS

Annual photographs can readily be used for analyzing the approximate year-to-year changes in a glacier's thickness. Three examples are described below, using lateral ice margins, the crest of the ice as seen in lateral views, and the crest of an ice bulge as viewed from down glacier.

In the first example, on each annual photograph in series 7 (selected years of which are shown in figs. 2–5) a smoothed line was drawn for a few thousand feet along the west ice margin [3] downstream from Wilson Glacier. The positions of several points on each marginal line were then defined by measuring down to them, on the pictures, from a series of fixed points (bedrock features) along the canyon wall identifiable on all the photographs studied. Next, the distances so measured were adjusted to the scale of the August 23, 1951, view, which year was selected as the year of minimum ice in that area. The scale adjustment was done by means of scale-ratio measurements made between several fixed points identifiable on all the prints. Using the converted distances, the lines were transferred to the 1951 print (fig. 6).

Most of these ice-margin lines are believed to be accurate to ± 20 feet (6 m) vertically or horizontally. The greatest source of error is in the subjective determination of the location of the margin of the active ice for each year because the margin is obscured in many places by varying amounts of remnant ice, snow, or rock debris.

In the series 7 photographs, the valley wall is about 3,300 feet (1,000 m) away from the camera opposite the middle of the nunatak and 7,500 feet (2,300 m) away just below Wilson Glacier. The approximate

[3] The margin is the apparent edge of the moving ice, whether it is obscured by detritus or not.

Figure 2.—Nisqually Glacier, from confluence with Wilson Glacier to the nunatak, as seen from station 7 in 1890 (date uncertain). (Figures 2–5 were photographed from the same viewpoint as was used for the photograph published in the Geological Survey's Annual Report for 1896–97 (Russell, 1898).) Note some similarities to 1963 view in regard to extent of ice and patterns of crevassing; note also the absence of a large moraine near the west canyon wall. Photograph is believed to have been taken in 1890 by W. O. Amsden, but may have been taken in 1896 by a member of the I. C. Russell (U.S. Geological Survey) reconnaissance party.

Figure 3.—Nisqually Glacier, from confluence with Wilson Glacier to the nunotak, as seen from station 7 in August 1915 by G. L. Parker, U.S. Geological Survey. This view was taken from a slightly different location than the others in series 7; it was higher on the hillside, with camera pointed farther to left. Note (as is graphically verified in fig. 6) how the conformation of the surface slope of the ice along the west canyon wall was different in 1915 than in 1963 or 1965, and how during the intervening half century many changes in exposure of the rock formations occurred. Note also the two moraines near far edge of glacier, marked by debris lines.

Figure 4.—Nisqually Glacier, from confluence with Wilson Glacier to the nunatak, as seen from station 7 on August 22, 1945. Upper part of glacier is at about its lowest known ice mass, as evidenced by the exposure of bedrock. There is almost no crevassing in middle reach. Slope at profile 2 (location in fig. 20) is very flat and broken below there. Note the light-colored medial moraine approaching nunatak from upper right. Sources of debris may be deduced. Note also large ice-cored moraine along west edge of glacier.

Figure 5.—Nisqually Glacier, from confluence with Wilson Glacier to the nunatak, as seen from station 7 on August 27, 1963. Note transverse crevasses developing in east part of glacier above nunatak indicating the direct down-valley movement of that ice. Ice-cored moraine seen in figure 4 is now subdued because of the rejuvenated movement. Note that since 1945 the glacier has recovered much of the volume evident in the 1890 view.

Figure 6.—Ice margins for selected years in period 1890–1965 are indicated on the series 7 photograph taken August 23, 1951. Note that by 1965 the glacier had recovered much of the ice thickness it had lost since 1890.

vertical scale of the valley wall on a photograph could readily be calculated from these distances and the camera's focal length.

In the second example of ice thickness analysis, data for the graphical plotting of the changes in ice-surface elevation at a single cross-profile axis were derived as follows. On each annual print of series 14–W (figs. 7–10) the distance was measured between a selected rock feature on the canyon wall directly opposite the photographic station and the ice margin directly below it. The results were converted to a common-scale basis with respect to the print for year of the lowest ice, 1951, as was described in the previous example, and the values were plotted graphically against time (fig. 11*A*) and compared with the thickness changes indicated by the annual cross-profile surveys. The graph of thickness changes measured on the photographs could not be given a vertical scale in feet (or meters) unless it were obtained by comparison with field survey results, as is this case, or by geometrical computation using map data and the camera lens focal length.

On the graph in figure 11*A* the scale of the photographic measurements was adjusted to closely fit the scale to which the field surveys were plotted. There are a few small inconsistencies between the field surveys and photographic measurements in figure 11*A*, probably due to the low vertical angle between the camera viewpoint and the distant ice margin which is not always clearly visible. Still, such a graph for a valley glacier lying between steep canyon walls is roughly indicative of the changes in ice thickness in the entire cross section of the glacier opposite the point of measurement.

A third example of a method of determining ice thickness variations from photographs utilizes the measurement reach indicated on the 1944 view in photographic series 15 (fig. 12) taken looking up glacier. In the annual photographs of series 15, distances were measured down from a bedrock feature to the crest, as seen from the photographic station, of a "standing" wave or bulge in the glacier surface nearly 4,000 feet (1,200 m) up glacier from profile 3 at an altitude of 8,400 ± 100 feet (2,560 ± 30 m). This bulge (fig. 12) occurs at the downstream end of a reach of relatively flat slope, and its crest is seen in profile when looking upstream from below. The distances so measured were plotted against time, using an estimated vertical scale, and thus their fluctuations were compared with the stadia surveys of profile 3 (fig. 11*B*). Though without a true vertical scale in feet (or meters), these results are indicative of the fluctuations in position of the ice surface at that site during glacier advance or recession. In this example the values are believed to be accurate to within plus or minus 25 feet (8 m).

It is most interesting that thickness changes were nearly synchronous at profile 3 and at the bulge 1.2 km above profile 3. The minor inconsistencies between the graphs in figure 11*B* may possibly be caused by differences in timing of the ice advances of Wilson Glacier with respect to those of Nisqually Glacier above Wilson Glacier. An attempt was made to check this timing, but the results were not satisfactory. The reason for this may be the small upward angle of view in the photographs of the top of any ice bulge on Wilson Glacier; they do not place the lip of the bulge sufficiently in outline or profile. Another source of inconsistency may be the irregular changing shape of the top of the ice bulge occurring from year to year.

CHANGES IN LATERAL ICE MARGINS

Some of the ice-thickness analyses in the preceding section also indicate changes in position of the lateral ice margins of the glacier. Such changes are further illustrated by lines around the nunatak as shown on an enlarged part of the August 22, 1951, view from series 6 (fig. 13). The ice margins for each of the selected years indicated were transferred by tracing from one single weight print to another, over a very bright light. All the annual prints used must be enlarged to the same scale.

The maximum error incurred in figure 13 is estimated to be ± 30 feet (9 m) measured along the surface of the ground rather than vertically or horizontally; the average distance from the camera is 2,500 feet (760 m), varying from about 2,100 to 2,900 feet (640 to 880 m).

It was found that the topographic maps and cross-profile survey results currently available for this glacier do not contain enough detail to permit the derivation of as accurate data on changes in the ice margins, in some areas, as can be determined from photographs.

LONGITUDINAL SLOPE OF THE ICE SURFACE

The photographs in series 14–W (figs. 7–10) were found suitable for obtaining measurements of longitudinal slope of the glacier surface at profile 2. On each annual print the angle of slope was measured by protractor with respect to a vertical line (figs. 7–10) projected on the canyon wall at far end of the profile. The position of this line was determined from a phototheodolite view that was taken by the Conservation Division of the U.S. Geological Survey and was checked from a photograph taken by the writer in which a plumb-bob line was suspended in front of the camera. It was interesting to find that the general slope of the glacier is deceiving to the eye; it is greater than it appears, and thus

Figure 7.—View across glacier in series 14–W (profile 2) used to determine slope and changes in ice thickness; photographed on August 21, 1942. The vertical line used in measuring angle of slope of the ice surface is shown. Not indicated is the bedrock feature from which the changes in ice-surface elevation were measured. The apparent crest of the debris-covered ice (arrow), rather than the white ice, was averaged to compute slope and changes in thickness in this and all other views in this series. Note that the hand-held camera had been tilted, due to the deceptiveness of the true slope of the glacier.

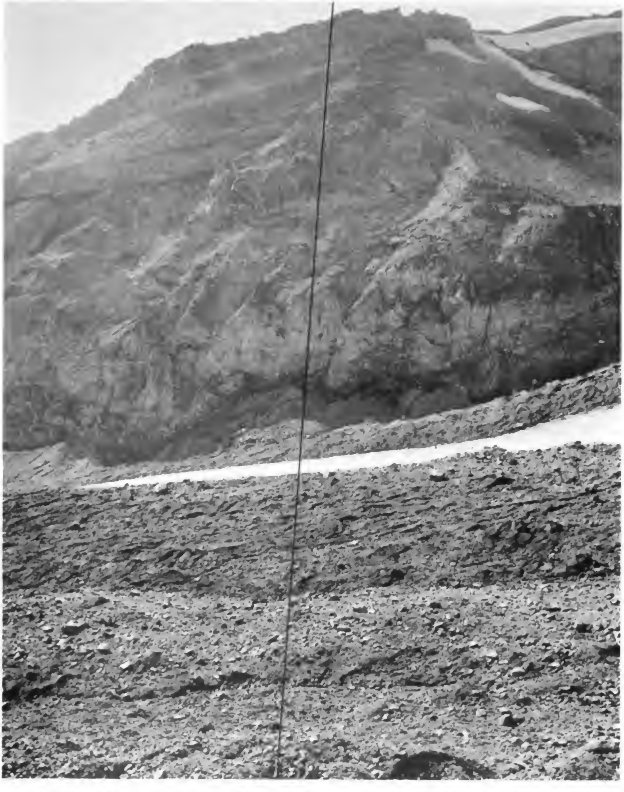

Figure 8.—View across glacier in series 14–W (profile 2) used to determine slope and changes in ice thickness; photographed on August 27, 1952. The vertical line used in measuring angle of slope of the ice is shown. Note the relief visible in the canyon wall, which is not at all apparent in the views that were taken in 1942, 1960, and 1965 under flatter lighting.

Figure 9.—View across glacier in series 14-W (profile 2) used to determine slope and changes in ice thickness; photographed on September 8, 1960. The vertical line used in measuring angle of slope of the ice is shown. Note that glacier surface in this area has become much rougher since 1952 (fig. 8), and the streak of white (clear) ice is now hidden behind the thickened zone of crevassed, debris-covered ice.

Figure 10.—View across glacier in series 14-W (profile 2) used to determine slope and changes in ice thickness; photographed on August 30, 1965. The vertical line used in measuring angle of slope of the ice is shown. Note that the crevassing is more pronounced than it was in the 1960 view (fig. 9), and there is less contrast between clear and debris-covered ice.

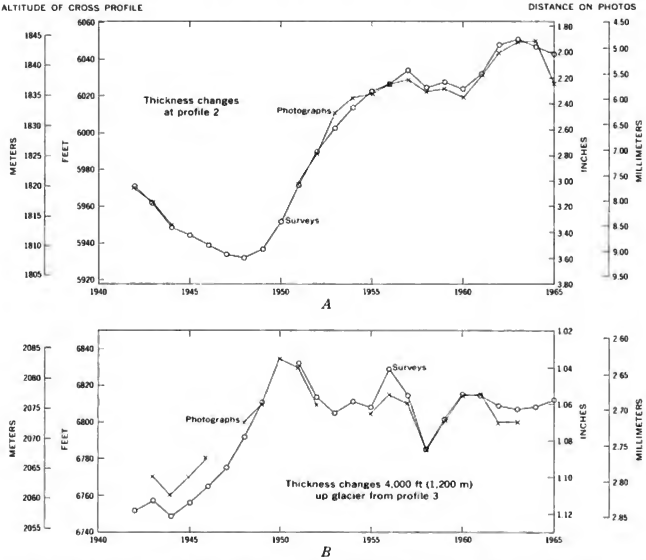

Figure 11.—Graphs showing changes in ice-surface elevation, or thickness, of the glacier. *A*, Changes in glacier thickness at cross profile 2 as measured on photographs are compared graphically with results of the annual stadia surveys. It should be noted that each stadia survey value used in the comparisons is the average ice-surface elevation along the cross profile, but each photographic measurement is made from a bedrock feature in the canyon wall down to only one point, selected in each photograph as either the apparent crest or a representative point useful for the purpose. *B*, Changes in ice-surface elevation as measured on photographs at an ice bulge nearly 4,000 feet (1,200 m) upglacier from profile 3 are compared graphically with the results of annual stadia surveys at profile 3. The values from photographs are obtained by measuring from a fixed point on bedrock down to the top of the ice bulge as it is seen in profile from down glacier at station 15 (fig. 12).

Figure 12.—Changes in ice thickness occurring about 4,000 feet (1,200 m) up glacier from profile 3, were measured on the photographs in series 15 in the reach indicated on this September 3, 1944, view from that series; upper end of measurement is the base of a lava flow and lower end is top of the ice. This 1944 view illustrates the general nature of the upper area after many years of recession had occurred, just preceding the ice advance of the late 1940's. The ice discharge from Wilson Glacier is low, and large areas of bedrock near its mouth are exposed. The falls at far left are relatively large compared with their condition in later years (1957–65). Note the opposite directions of cleavage in crevassing patterns which are visible in midglacier at lower left. It is evident that the debris load comes from sources along both sides of Nisqually Glacier and from Wilson Glacier. Bedrock areas marked by small X's were inundated by ice as the glacier thickened and expanded (compare with fig. 34 which shows this area in 1965).

Figure 13.—Ice margins around the nunatak for selected years in the period 1942–65 are indicated on the August 22, 1951, photograph taken from station 6. The down-glacier parts of the 1942, 1961, and 1965 lines are indeterminate because the ice is obscured by debris.

makes the photographer unconsciously tilt a hand-held camera a little in a down-glacier direction.

A protractor was placed along the apparent crest of the dark ice in each picture on a reach 100–200 feet (30–60 m) in length. On a few of the annual prints, the top of the white ice near the far margin of the glacier may have been better than the dark ice as an index of the slope, particularly on the print for 1952 (fig. 8), where the white ice surface is especially prominent and is about 2 degrees steeper than the dark ice. However, in the photographs for most other years, the white ice either is too obscured or could be confused with the glacier's margin, so it was not used.

For comparison with the photographic results obtained from 1942 to 1965, slope values in the same period were determined from topographic maps for 1941, 1946, 1951, 1956, and 1961. (See fig. 14.) On each map a 200-foot (60-m) reach was used, drawn along the same ice ridge as appeared in the corresponding photograph to be the crest of the ice. Elevations between contours were interpolated. The results for 1951, 1956, and 1961 probably are more accurate than those for 1941 and 1946 because of the more refined procedures used in making the later maps. The results were used (Meier, 1968) in a study of the flow and stress in Nisqually Glacier.

The slope values obtained from maps are somewhat greater, by about 2 degrees, than the corresponding values measured on photographs. This is believed due to a lack of sufficient detail in the maps for this kind of a study; they do not completely reflect the short reach of flattened slope that occurs in the immediate vicinity of profile 2 in the east half of the glacier, which is discernible in some photographs. (See fig. 4.) See also the generalized slope values for the glacier given in the tabulation on page 5.

One source of error in the measurement of glacier slopes on photographs, under conditions similar to those at profile 2, is the effect of varying vertical angles of camera view that result from the different stages of the glacier. During the 18 years covered by this analysis, the mean altitude of the glacier surface along profile 2 fluctuated below the camera viewpoint at station 14 by amounts ranging from 110 to 240 feet (34 to 73 m). Thus, because of the downward angle of camera view, the longitudinal ice-surface profile appearing on the prints to be the crest probably lies on the far side of the true crest. In addition, as the glacier surface rises and falls from year to year the crest seen on the photographs may shift laterally toward and away from the camera or, by chance, may lie at an angle to the main flow lines of the glacier.

The above factors create some relatively minor errors when glacier slopes measured on photographs are compared with those obtained from contour maps. However, the fact that the changes in slope obtained by the two methods are reasonably consistent with each other indicates that the photographic method, which is relatively low in cost, is accurate enough to be a useful and valuable accessory in a reconnaissance study of glacier slope.

Additional comments on the slope of the glacier are contained in the section "Crevassing and General Character of Glacier Surface."

SNOW LINES AND FIRN EDGES

Oblique photographs of a glacier taken from stations on the ground along only one side of a glacier were found to have but limited value for mapping and analyzing the boundaries of snow and firn. These photographs give fairly satisfactory coverage for that purpose on the full width of the glacier up to an altitude of about 5,800 feet (1,800 m), and on its eastern half up to about 6,700 feet (2,000 m). However, at higher

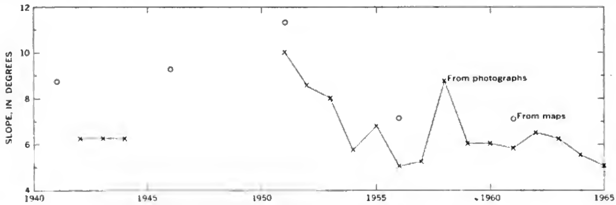

Figure 14.—Determinations of longitudinal slope of the glacier surface at profile 2, as measured on the annual photographs taken from station 14-W, are compared graphically with those measured on the 5-year series of topographic maps.

altitudes some parts of the glacier surface are obscured by ice bulges or moraines or by slopes dipping away from the position of the camera. So, when these lines are to be mapped and it is not economical to have photographic stations at rather high altitudes on both sides of a glacier, it would be better to obtain aerial photographs.

In this report the lower edge of the snow is called the snow line, and the lower extremity or edge of the firn is called the firn edge. (See also footnote 1, p. 1.) The wide range in annual altitude of the snow line and firn edge on Nisqually Glacier from 1942 to 1965 and their extremely broken appearance are evident in the various photographs published herein. On a 1955 picture (fig. 15) taken from station 13 a few of the firn areas have been outlined to illustrate their scattered occurrence. Location of the firn edge ranged from about 6,000 to 7,300 feet (1,880 to 2,250 m) during the period covered by these photographs.

Position of the snow line in late summer of each year has been found to range between about 5,800 and 7,300 feet (1,750 and 2,250 m). An example of a well-defined snow line on this glacier is seen in the 1942 view in series 5 (fig. 20), where but little snow remained below 7,000 feet (2,100 m).

QUALITATIVE INTERPRETATIONS

CHARACTERISTICS OF THE TERMINUS

The terminus of Nisqually Glacier has been illustrated by photographs since 1884. These complement the field surveys by showing in more detail the irregularities of the terminal margin and by indicating its approximate position during periods when no surveys were made. For example, figures 16 and 17 show that the glacier terminus near the falls at left was in a more advanced position in 1908 than in 1903.

The dynamic condition of a glacier's snout also is revealed by photographs (Meier and Post, 1962). By its characteristic bulging, crevassed, "fat" appearance an advancing terminus (fig. 16) usually can be distinguished from a retreating terminus (figs. 17–19). If a glacier is receding or stagnant, the front has fewer crevasses and is more gently sloping; it may be segmented as is shown in the 1962 picture in series 5 (fig. 24) where the advance of fresh ice is visible upglacier but has not yet affected the dead-ice terminus. Ice hummocks on the glacier (fig. 17) also indicate a wasting condition. The "sliced-off" appearance of the terminal front shown in figure 18 has been typical of Nisqually Glacier's stagnant terminus during its long recession. For further illustration of changes in the glacier's terminus, see figures 20–25.

The photographs in this report, when viewed in the light of contemporaneous field survey results, show that the appearance of a glacier's terminus is roughly indicative of its dynamic state; however, the terminus does not reflect any condition upstream from the terminal area. Further, annual pictures of the snout do not necessarily reveal the presence or absence of movement of the terminus. For example, while photographs might illustrate the occurrence of a net recession of 30 feet (9 m) in a 12-month period, this could have resulted from 10 feet (3 m) of forward movement accompanied by 40 feet (12 m) of melting, or 70 feet (21 m) of forward movement offset by 100 feet (30 m) of melting.

DEBRIS COVER AND ITS DISTRIBUTION

Annual photographs are useful in a study of the changing patterns of debris carried on a glacier's surface. Examples of information about debris readily observable on the Nisqually Glacier photographs are as follows.

The 1945 view in figure 4 shows that the extensive load of debris carried on the east side of Nisqually Glacier between altitudes of 5,700 and 7,000 feet (1,740 and 2,130 m) originates from Nisqually Cleaver west of Gibraltar Rock, from the southwest slopes of Gibraltar Rock and Cowlitz Cleaver, and from the downglacier hillsides bordering the east side of the glacier. In years of above-average snowfall such as 1890 (fig. 2) and 1954 (fig. 22) this mantle of debris was obscured by snow as far down the glacier as about an altitude of 5,800 feet (1,800 m).

The photographs in figures 20–25 also indicate that the insulating effect of debris was responsible for development of the debris-covered, high, morainelike ridge of ice which was visible for many years near the west edge of Nisqually Glacier downstream from Wilson Glacier; and they show how this ridge later became obscured during the new ice advance.

Changes in debris conditions are also illustrated in figures 27–34, and described both in the picture captions and in the section "Crevassing and General Character of the Glacier Surface."

MORAINES

Photographs may bring out some detailed moraine and erosion patterns not noticed by an observer on the ground because film can emphasize color values and relief otherwise not very apparent. The pictures for different years can readily be examined and compared with respect to subtle features, which may easily be forgotten if observed only during occasional field inspections. An example of such a feature is the light-colored band in the large medial moraine near the east side

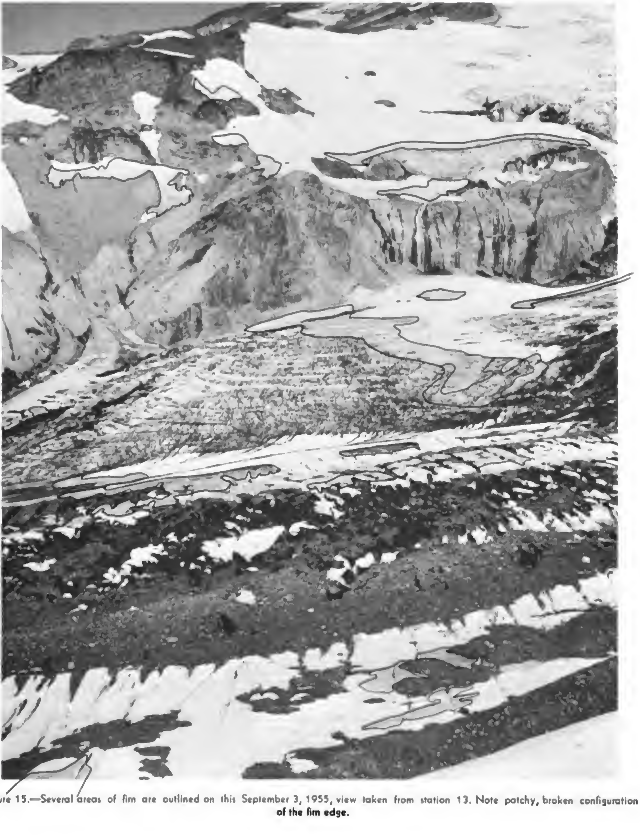

Figure 15.—Several areas of firn are outlined on this September 3, 1955, view taken from station 13. Note patchy, broken configuration of the firn edge.

Figure 16.—Photograph of the terminus selected from series 1–NE, taken from a point at or near the old highway bridge in 1903. Note bulging shape of terminus, steepness of downstream face, and the vertical crevassing pattern. These characteristics suggest that the terminus is, or has very recently been, advancing. Photographed by Eugene Ricksecker; furnished by the National Park Service.

Figure 17.—Photograph of the terminus selected from series 1–NE, taken from a point just below the old highway bridge in 1908. Note changes in terminus with respect to 1903 photograph. At upper left the bulging ice has been replaced by ice hummocks; the crevassing pattern on downstream face is no longer predominately vertical; ice surface now has the general appearance of being melted and eroded. These conditions suggest that the advance has ceased and the terminus has begun to recede. Photographed by Mr. Leftbetter of Seattle; furnished by Tacoma City Light.

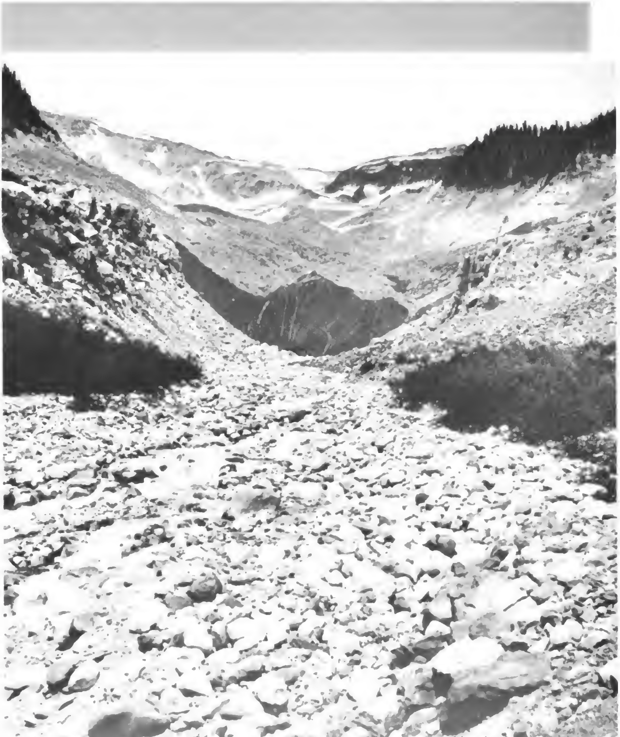

Figure 18.—Photograph of the terminus selected from series 1–NE, taken from a point at or near the old highway bridge on July 5, 1929. In marked contrast to the 1903 and 1908 appearances, the noncrevassed, "sliced-off"-looking terminal face and the generally concave, debris-covered condition of the surface above indicate that the terminus is now definitely receding and is approaching a stagnant condition.

Figure 19.—Photograph of the terminus selected from series 1–NE, taken from a point at or near the old highway bridge on August 19, 1942. The terminus is now more irregular and segmented than in 1929. This suggests stagnation, as there is little evidence of ice flow to the terminus from above. The rate of melting is probably reduced because of the extensive debris cover.

Figure 20.—Lower part of Nisqually Glacier as seen from station 5 on August 31, 1942. Approximate locations of the surveyed cross profiles are shown. Entire glacier is receding. Area down glacier from profile 1 (lower end of the white ice) is stagnant, as indicated by hummocky, debris-covered, noncrevassed ice. Note the long morainelike ridge of debris-covered ice immediately to left of the white ice. The nunatak is bare. Note debris load on right half of the glacier from profile 3 downstream.

Figure 21.—Lower part of Nisqually Glacier as seen from station 5 on August 22, 1951. Since 1942 the glacier has thickened by about 80 feet (24 m) at profile 3 and 40 feet (12 m) at profile 2, but it still is thinning at profile 1. Note the lateral melting of ice ridge to left of the nunatak, as compared with the 1942 view, and the exposed river bed.

Figure 22.—Lower part of Nisqually Glacier as seen from station 5 on September 1, 1954. This is the year of minimum ice mass at profile 1 where, according to surveys, the glacier surface has dropped 13 feet (4 m) since 1951; at profile 3 it has dropped 21 feet (6 m), but at profile 2 the glacier is now 42 feet (13 m) thicker than in 1951. Note steep front of the vigorous advance of fresh ice which is passing to left of the nunatak. Downstream from there the ice is "dead" and melting away—slowly, however, owing to its insulation by a thick mantle of debris. Surveys show that 1954 is the first year when a segment of the ice surface near the west end of profile 1 began to rise.

Figure 23.—Lower part of Nisqually Glacier as seen from station 5 on September 11, 1959. With respect to its 1954 condition the glacier now is 9 feet (3 m) thinner at profile 3, 12 feet (4 m) thicker at profile 2, and 70 feet (21 m) thicker at profile 1. The stagnant ice terminus now is visible at lower left. Fresh, white ice has nearly obscured the debris-covered ice ridge opposite the nunatak near the left (west) edge of the glacier.

Figure 24.—Lower part of Nisqually Glacier as seen from station 5 on September 8, 1962. Profile 3 is 7 feet (2 m) higher than in 1959, and since then the glacier has thickened 22 feet (7 m) at profile 2 and 24 feet (7 m) at profile 1. The broad bulge of thickening is visible in midglacier in the vicinity of profile 2. The nunatak has been topped by flowing ice. Dead ice downstream has receded considerably since 1959, but now previously stagnant ice in midchannel is thickened and has been incorporated in the advancing terminus.

Figure 25.—Lower part of Nisqually Glacier as seen from station 5 on August 30, 1965. With respect to its 1962 condition the glacier has gained 3 feet (1 m) in thickness at profile 3 and lost 5 feet (2 m) at profile 2; however, at profile 1 the thickness has increased 34 feet (10 m). The preliminary result now available for the 1966 survey shows that 1965 was a peak year at profile 1. The vigorous terminal reach and snout of the glacier have completely covered or incorporated all vestiges of stagnant ice. The nunatak is almost entirely engulfed.

of the glacier in figure 4. Another example is shown in the 1940 photograph taken from station 12 (fig. 26), which illustrates several small lateral moraines that had been deposited along the east side of the glacier at an altitude of 6,400 feet (1,950 m), suggesting a discontinuous rate of recession of the glacier.

CREVASSING AND GENERAL CHARACTER OF THE GLACIER SURFACE

In addition to the data presented in the preceding sections, some further examples of what photographs can show about glaciers are given below on the following subjects (all of which have not been studied herein in detail):

1. Crevassing patterns, from which the nature of the subsurface structure, the direction of ice movement, and changes in rates of movement can be interpreted.
2. Information of changes in surface slope, or the shape of its longitudinal profile, in areas not covered by surveys and contour maps.
3. Some details about advance, recession, debris load, contour, movement, thickness, and surface erosion.

Terminus to profile 1

Photographic series 1–NE (figs. 16–19) and 5 (figs. 20–25) illustrate the gradual deterioration and shrinkage of the entire glacier downstream from the nunatak and profile 1, and its subsequent reactivation. This lower area was virtually stagnant from about 1944 to 1954, but a spectacular advance of fresh ice passed the nunatak in 1954–55 and reached the terminus in 1963. By 1965 it had given form to a new, vigorous-looking terminus.

Profile 1 to about 1,000 feet (300 m) above profile 2

Captions for the photographs in series 6 (figs. 27–31), 7 (figs. 2–5), and 14–W (figs. 7–10) contain miscellaneous descriptive comments for this reach of the glacier. Certain features can be seen more clearly in one series than in the others. The following comments about the photographs in series 6 and 7, arranged in chronological order for each series, include most of the descriptive material that is contained in the captions:

Photographic series 7 (figs. 2–5)

1890 The glacier above the nunatak is at the highest stage ever known to have been photographed.

1915 Note the debris-covered moraines along far side of glacier, which were not visible in 1890. The nunatak (at lower right) still is covered by ice.

1945 Nunatak is exposed. Slope at profile 2 is almost flat. Light-colored band of debris shows in medial moraine at right center; Wilson Glacier ice discharge is very low. There is almost no crevassing in middle reach.

1963 Crevassing in midglacier near profile 2 is extremely coarse or rough. Ice level at profile 2 is the highest in nearly 30 years. Direction of the crevassing pattern in east part of glacier above the nunatak, when compared with that in figure 27, indicates that as the nunatak becomes submerged a lesser proportion of the east-half discharge is diverted toward the west canyon wall.

Photographic series 6 (figs. 27–31)

1952 White-ice stream at left has much more uniform slope than in 1945. This is first year since the early 1940's when fresh crevasses have appeared in midglacier above the nunatak. Their direction, at a steep angle to the general direction of ice flow, indicates strong longitudinal shearing above the nunatak caused by more vigorous flow in the east half of the glacier.

1954 New ice front is passing the nunatak. Note severity of the crevassing upstream and its continued angling (since 1952) with respect to the valley axis.

1958 Ice level at profile 2 peaked in 1957; at profile 1 it remained constant for 4 years before again advancing in 1962. The slope at profile 1 appears rather steep. In this photograph there is a good portrayal of the ablation of crevasse walls.

1961 See large patch of debris at lower left which has greatly increased since 1958. A flat reach appears to be forming in white-ice slope above profile 2. Nunatak is being topped with ice.

1965 Profile 2 appears to be on a long reach of rather uniform slope, with flat slope occurring not far upstream from there. Nunatak is almost entirely engulfed with thick ice. This year the ice level at profile 1 is highest since about 1938.

1,000 feet (300 m) above profile 2 to above profile 3

For comments about this area, see captions of the photographs in series 15 (fig. 12) and 13 (figs. 32–34). Series 15 provides some coverage of upper part of glacier for the period prior to 1949, before series 13 was begun. A summary of the comments contained in the captions follows:

Series 15 (fig. 12)

1944 Glacier is nearing the end of a long period of recession, and at this stage there is very little crevassing. The inflow of ice from Wilson Glacier is low; note the large exposures of bedrock. A heavy load of debris is being carried, contributed from both banks of Nisqually Glacier.

Series 13 (figs. 32–34)

1949 This picture was taken from a point about 500 feet (150 m) upstream from the station where remainder of the series was taken. Crevassing pattern has expanded since 1944, especially in areas nearest the camera station. Bedrock outcrops at lower end of Wilson Glacier are nearly covered.

1957 Glacier surface at profile 3 is 10 ft (3 m) higher than in 1953; ice field at top of cliff at left is much thicker. Crevassing now extends to east edge of the glacier.

1965 Surface of glacier in general appears a little smoother and slopes less steep. Firn can be seen in several areas. Ice on cliff at left appears about the same as in 1962.

Figure 26.—Patterns of small recessional lateral moraines on east bank at an altitude of about 6,400 feet (1,950 m) are evident in this 1940 view taken looking up glacier from station 12. The patterns suggest that at times the recession progressed in a discontinuous manner, as in successive small steps interrupted by slight advances. Photograph by F. F. Lawrence, Conservation Division, U. S. Geological Survey, August 26, 1940.

Figure 27.—Nisqually Glacier near the nunatak, as seen from station 6 on August 27, 1952. Note long reach of smooth-appearing, convex-upward slope of the white ice, terminating in smooth black ice. Effect of advancing new ice now has nearly reached the nunatak, as evidenced in midglacier by the pronounced new (sharp-edged) crevassing. Stream bed shows both to left and right of nunatak.

Figure 28.—Nisqually Glacier near the nunatak, as seen from station 6 on September 1, 1954. Practically all the main ice flow from east half of glacier is being diverted to west side of the nunatak. Note steep front of the fresh ice advance.

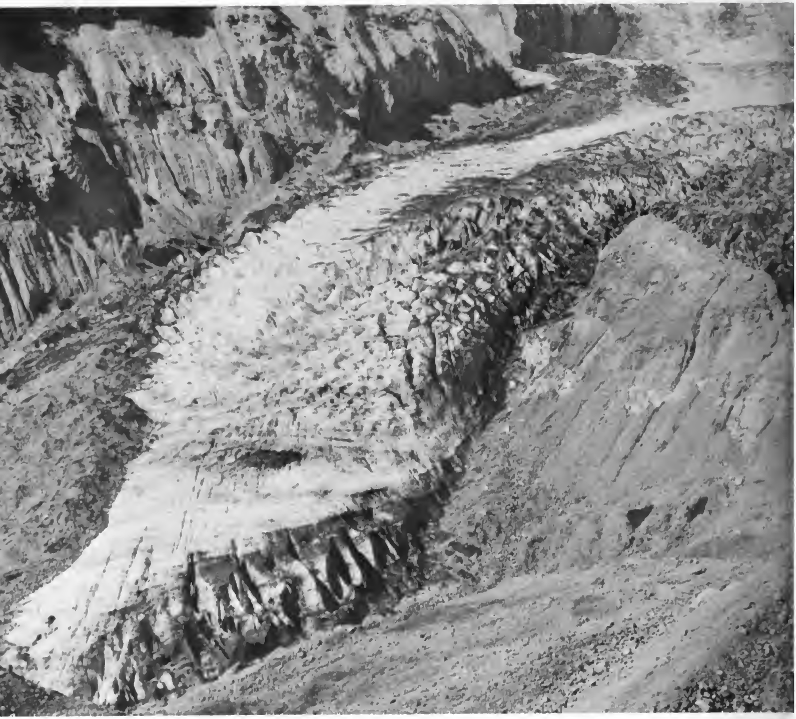

Figure 29.—Nisqually Glacier near the nunatak, as seen from station 6 on September 5, 1958. Note growth and movement of ice over peak of nunatak and along its east side which have occurred since 1954. Crevassing in midglacier in the vicinity of the nunatak has a very coarse pattern, and this photograph is a good portrayal of the ablation of crevassed walls. This was a summer of obnormally high ablation. The ice-cored, morainelike ridge noted at left in the 1942 view in series 5 (fig. 20) has nearly disappeared.

Figure 30.—Nisqually Glacier near the nunatak, as seen from station 6 on September 6, 1961. Note finer pattern of the crevassing in comparison with 1958, and the large patch of debris on ice at lower left. Slope at profile 2 appears reduced. This is the fourth consecutive year, beginning with 1958 (fig. 29), in which surveys show that the elevation and slope of the glacier surface from profile 2 to profile 1 have remained nearly constant.

Figure 31.—Nisqually Glacier near the nunatak, as seen from station 6 on August 30, 1965. Crevassing patterns this year are generally coarser than in 1961. This wave of ice advance which is engulfing much of the nunatak reached a peak at profile 2 in 1963 and at profile 1 in 1965. Photographs show that a substantial part of the east-half discharge is now continuing straight down glacier parallel to the valley margins, in contrast to the 1952–54 conditions of nearly complete diversion to the west. See also figures 5 and 25. The large patch of debris visible in 1961 has gone, but debris still is surfacing just to left of nunatak. Debris mantle again is continuous in reach along west canyon wall where an ice ridge formerly existed.

Figure 32.—Upper reaches of Nisqually and Wilson Glaciers as seen from station 13 on August 28, 1949, taken several hundred feet (say 150 m) up glacier from station 13. Location of profile 3 is shown. Along profile 3 the surface of the ice is 62 feet (19 m) higher than in 1944 (fig. 12); 19 feet (6 m) of this was added since 1948. Crevassing is becoming more extensive. Bedrock outcrops at the mouth of Wilson Glacier are nearly covered. Many of the bedrock outcrops noted with X's in figure 12 (1944) are already covered by the expanding glacier.

Figure 33.—Upper reaches of Nisqually and Wilson Glaciers as seen from station 13 on August 30, 1957. Most of exposed bedrock areas marked in figure 12 (1944) are now covered by Wilson Glacier. Glacier surface at profile 3 is only 3 feet (1 m) higher than in 1949, but near left edge of picture it probably is about 60 feet (18 m) higher because at profile 2 the ice level rose 97 feet (30 m) from 1949 to 1957. The crevassing appears much coarser (rougher) now and extends to the east edge of the glacier. Exposed face of the ice field above the cliff is thicker. The falls at far left are nearly dry (compare with fig. 12). Note the different layers (ages) of firn exposed in the small area at lower right, which can be differentiated by various shades of gray.

Figure 34.—Upper reaches of Nisqually and Wilson Glaciers as seen from station 13 on August 30, 1965. The glacier from profile 3 downstream to where it leaves this view has now reached a steady-state condition, as determined by the annual surveys. In general the crevassing appears similar to that of 1957. Firn can be seen in many areas. Ice on cliff at left is much thicker than in 1957.

EROSION AND DEPOSITION

Banks and lateral moraines

Annual photographs reveal the progress of erosion along the banks of a valley glacier and along old lateral moraines. The 1947 and 1965 views in series 11 (fig. 35) illustrate 18 years of erosion of west side of the old east-bank lateral moraine. Along this part of the moraine the average lateral recession of its crest over the 18-year period has amounted to a total of 10–15 feet (3–5 m).

In regard to erosion of the banks of a glacier, the views in series 14–W (figs. 7–10) show how some of the bedrock areas on the steep hillside above the west end of profile 2 became unrecognizable within 20 years. Note changes in the lower rock formations seen in the 1942 and 1960 views, which were photographed under similar light conditions. Thus, on photographs of a canyon wall, it may be difficult to pick out bedrock features that will be usable as long-term landmarks for measurements in photographic studies. In the present study, a few usable points were found that could be identified on pictures throughout the 24-page period of record.

Outburst floods

Repetitive photographs also portray changes in topography and vegetation in the channel and valley below a glacier that result from outburst-type floods (jökulhlaups). Three such floods emanating from Nisqually Glacier are described briefly below.

Flood of October 14, 1932. This flood tore away the reinforced concrete arch bridge which had been constructed in 1926. A precipitation total of 6.90 inches (175 mm) fell at Paradise Ranger Station October 10–13, inclusive. It is interesting to note what apparently is the deck of that bridge clearly visible in the 1947 view (fig. 37) in series 3 (figs. 36–38), just below the tree-covered island near the center of the picture.

Flood of October 24–25, 1934. A series of outburst surges from the glacier, according to the monthly report of the Superintendent, Mount Rainier National Park, dated November 5, 1934, "completely plugged the bridge and piled rock and debris 15 feet deep on top of the arch. Approach roads on both sides of the bridge were washed out." Precipitation of 8.92 inches (227 mm) occurred at Paradise Ranger Station October 20–25, inclusive. This bridge, less than 2 years old and situated at the same site as the bridge it replaced after the 1932 flood, was reconditioned and used until its washout in 1955.

Flood of October 25, 1955. The flood occurred about noon and destroyed bridges and other property downstream. It was preceded by heavy rainfall (a total of 5.51 inches (140 mm) was measured on the 24th and 25th at Paradise Ranger Station) and was observed by a Park Ranger to flow in several large surges. The frontal wave of the first surge was estimated to be 20 feet (6 m) high, and the water carried many large rocks and chunks of ice that were visible at the surface. The first surge tore from its abutments the heavily reinforced 80-foot (24-m) span, concrete highway bridge.

Natural changes below glacier from floods and other causes

The 1934,[4] 1947, and 1965 pictures in series 3 (figs. 36–38) illustrate the removal of vegetation, channel widening, and subsequent killing of trees that occurred for a few thousand feet (500–1,000 m) below the bridge as a result of glacier floods of the early 1930's and 1955.

The flood channel in the vicinity of the highway bridge was widened by the 1955 flood, and some vegetation was removed, as illustrated by the 1949 and 1956 views in series 2–S (figs. 39*A*, *C*). Margins of the flood plain and vegetation as they existed a month before the flood are indicated by white lines in figure 39*C* (1956). Note also the automobile-size boulders that were cast up onto the parking area just to left of and above the bridge, and the much larger boulder deposited upstream. Many large trees downstream from the bridge were washed away.

The annual photographs in series 2–S (only a few of which are shown in this report) show some interesting variations in the configuration of the low-flow channel between the glacier terminus and the highway bridge. They reveal how within one season the channel would change from meandering to straight, or vice versa, then retain one form for several consecutive years. An example is evident from a comparison of the photographs shown as figures 39*A* and 39*B*, for 1949 and 1950. Note also the new terraces visible in 1950 along the flood plain. Each subsequent annual view showed that the channel remained straight from 1950 until after 1953 (which was the last view taken until 1956).

A tributary alluvial fan, first visible in 1960, was deposited on right-bank flood plain above the bridge; by 1965 (fig. 39*D*) it had become a little larger.

The 1932–36 photographs taken by the National Park Service looking upstream from the bridge, which are not published here, indicate that the flood of October 1934 was very substantial and erosive above the bridge as well as in the vicinity of the island 1,000 feet (300 m) downstream.

[4] This "1934" undated photograph closely matches the appearance of the glacier terminus in a National Park Service photograph dated September 5, 1934. The match is fair, but less perfect, with their 1933 photograph; it is clearly poor with their October 1, 1932 photograph. Thus it seems likely that this "1934" picture, upon which the large amount of downstream flood plain vegetation is visible, was taken after the 1932 glacier outburst flood and before the October 1934 flood, when denudation of that vegetation probably took place.

Figure 35.—Erosion of old (pre-1840) lateral moraine on east side of the glacier is shown by the series 11 photographs of August 25, 1947 (upper), and September 4, 1965 (lower). The total erosion during the period 1947–65, indicated by black line on the 1947 view, appears to have averaged between 10 and 15 feet (3 and 4 .5 m) horizontally.

Figure 36.—Nisqually valley below the glacier, as seen from station 3 in 1934 prior to October flood (date estimated; see footnote 4, page 44). Photograph furnished by Conservation Division, U.S. Geological Survey. Note substantial stand of trees and brush on west part of flood plain, and river on east side of flood plain.

Figure 37.—Nisqually valley below the glacier, as seen from station 3 on August 25, 1947. West of the island of trees, most of the vegetation present in 1934 view is gone, due to glacier outburst flood of October 1934. The river now flows west of this island of trees. The deck of the concrete highway bridge used prior to the October 13, 1932, flood is visible on flood plain just below island of trees (arrow).

Figure 38.—Nisqually valley below the glacier, as seen from station 3 on August 31, 1965. Aggradation on the flood plain, caused by the outburst flood of October 25, 1955, is evidenced by altered topography and dead trees. A new bridge was constructed high above the flood-affected channels.

CONCLUSIONS

The information and data on glacier characteristics and changes contained in this report are believed typical of what can be derived from a long-term record of annual photographs. A summary of the findings follows:

1. Data on changes in ice margins are readily obtainable from photographs. Likewise, changes in glacier thickness can be derived either from the positions of the ice margins along a canyon wall or from measurements made on the photographs of distances from a bedrock feature down to a bulge in the ice surface, with the latter photographed as a profile or "silhouette" from below. Both methods check well with the results of stadia surveys; values from the second method probably are accurate in this area to within plus or minus 25 feet (8 m).
2. Annual values of the surface slope at profile 2 were measured on photographs and are believed to be at least as accurate as those determined from the contour maps. Absolute values of the slope ranged from 5 to 10 degrees. A photographic analysis of slope can be made rather accurately from annual pictures provided there is established by field surveys the projection of a reference vertical line on the canyon wall directly opposite the picture station, identifiable on each print with respect to enduring landmarks. Also, the photographic station used must not be much higher than the glacier surface.
3. Position of the summer snow line on Nisqually Glacier was found to range between altitudes of about 5,800 and 7,300 feet (1,750 and 2,250 m), whereas the firn edges appeared to be between altitudes of about 6,000 and 7,300 feet (1,850 and 2,250 m). However, the snow lines and firn edges on this glacier usually are very irregular. Aerial photographs or a more complete coverage of ground photographs than is available for this project would be needed for an analysis of the snow and firn limits in relation to climatic fluctuations.
4. Photographs are helpful in analyzing the rates of retreat and advance of a glacier's terminus and in distinguishing an advancing terminus from a retreating one, through illustration of the characteristic appearance of each. If advancing, the front of the terminus is steep, bulging, and crevassed; if receding or stagnant, it usually has a noncrevassed, more gently sloping appearance or it may become hummocky or segmented.
5. The pictures portray the appearance of a wasting glacier, including its stagnant lower reaches, during the latter part of a long period of recession. Later, they illustrate waves of fresh ice advance which engulfed the nunatak and replaced the segmented, stagnant terminus by a bulging, crevassed "fat" looking front.
6. Photographs illustrate the occurrence, nature, and changes in moraines and debris-covered ice ridges. They also show the sources, distribution, and general nature of the debris carried on a glacier's surface.
7. The dynamic condition of a glacier is indicated quite well by the nature and pattern of the crevassing as well as by the general character of the glacier surface. During ice advances, the crevasses are larger and coarser in pattern than during a recession. A hummocky surface reflects the wasting and ablating condition of stationary or receding ice, as is shown on the photographs.
8. Information about the progress of erosion on the banks and lateral moraines of a glacier can be determined from annual photographs. Canyon wall bedrock features change more rapidly than might be supposed.
9. Some of the effects of glacier outburst floods, often more damaging than is realized, are illustrated by the photographs in this report. The removal or killing of many large trees and the deposition of enormous boulders are shown.

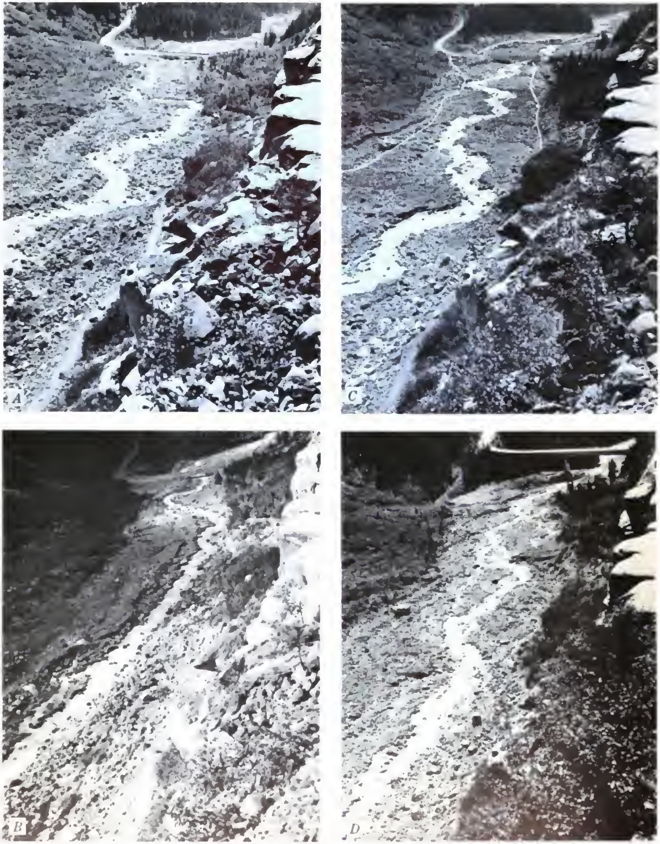
A
C
B
D

Figure 39.—River channel just above the highway bridge, as viewed downstream from station 2 on cliff.

A, August 28, 1949. Channel conditions illustrated in this view are about the same as those shown in the unpublished 1943, 1947, and 1948 photographs. No major outburst floods occurred in this period. Scale in vicinity of bridge is indicated by cars on parking area at left.

B, August 27, 1950. The relatively minor channel changes occurring between 1949 and 1950 still are larger than noticed for any other 12-month period not having a large outburst-type flood. The low-flow channel has become straightened and slightly degraded since 1949, and a few terraces and bars have formed along the left flood plain.

C, August 28, 1956. The October 25, 1955, glacier outburst flood has caused easily recognizable changes in the channel: 1, large (13 by 19 by 25 ft, or 4 by 5.8 by 7.6 m) boulder deposited at left; 2, wider swath cut through vegetation (edges of vegetation before flood indicated by white lines); 3, terrace formed along left side of flood plain; 4, many large boulders (one was 8 by 8 by 15 ft, or 2.6 by 2.6 by 4.9 m) deposited high on left bank above and below highway. Compare with fig. 39 A.

D, August 31, 1965. In the 9-year interval since 1956 note the following: 1, exceptionally large boulder at left has not moved; 2, small terraces are visible at left, caused by moderate-sized floods; 3, an alluvial fan (first visible in 1960) has been deposited by a right-bank tributary this side of the bridge.

RECOMMENDED PHOTOGRAPHIC PROCEDURES

PHOTOGRAPHIC STATIONS

When photographic stations are being selected, possible changes in the glacier and in nearby vegetation should be anticipated. Enough stations should be selected so that, if some should be destroyed or obscured, good views of all study areas including the terminus will still be afforded from other sites as the glacier advances or recedes.

All parts of the glacier subject to analysis should be photographed from at least two different viewpoints, if feasible. Where a particular reach is subject to study, every part of each ice margin in that reach should be visible in at least one picture.

For a study of surface slope from photographs, the station should be about the same elevation as the glacier surface and, if possible, where permanent features such as bedrock strata or outcroppings can be recognized in the background. If an ice advance should block the view from such a station, photographs taken at a higher altitude on an extension of the same cross-profile axis should be satisfactory for continuing the record of slope measurements.

Where stations are not on bedrock, the possibility of encroachment by vegetation or destruction by erosion should be considered. The site should be located in reference to two or more witness rocks in the vicinity. Stations should be marked with monuments such as bronze tablets or steel stakes, which are easily recognized.

When setting up a program of this kind it is better to establish too many rather than too few photographic stations. Some stations can always be dropped, but once any photographic records are missed they are lost forever.

OPTIMUM LIGHT CONDITIONS

Ideally, glacier photography should be scheduled so that the same lighting conditions occur every year at each station. To accomplish this, the photographs should be taken at about the same time of day and on about the same date each year. Without such uniformity in lighting, the changes illustrated in a series of pictures are difficult to analyze, and interpretations may be misleading.

At stations where photographs are taken in several directions, there may be no entirely satisfactory time of day for all of the views. Furthermore, the scheduling of photographs at a series of stations must be adjusted to fit the practicable time of travel from place to place, thus requiring some compromise with the desired light conditions.

When a particular view is found to be blocked or shaded by fog or clouds, it still is advisable to take a picture even though another photograph might be obtained later under better conditions. The first picture may be of poor quality, but perhaps it could be used for study if none other should become available.

SELECTING THE VIEW

The best direction of view at a station should be selected the first year, taking into account the probable movements of the glacier, and then repeated each year without change. The exact site over which the camera is placed should be identifiable by a permanent marker, and the camera should be positioned within a foot of the same location each year. When pointing the camera, it is helpful to refer to an earlier photograph that shows the desired view at the station.

Panoramic views should overlap 20 to 30 percent so that the photographs when trimmed will match satisfactorily. The transverse axis of the camera should be held in a level position, adjusting the view as necessary by raising or lowering the camera's front but without tilting it sideways.

EQUIPMENT

The camera should be sturdy and equipped with a lens that permits high resolution over the entire image and a minimum of optical distortion toward the corners

of the picture. It is understood that, as a general guide, the best results from a good lens will be obtained when its aperture is closed two to four stops from its maximum opening. Therefore, under a condition of intense light such as is available at a glacier, a rather slow film is preferable so the middle range of lens openings can be utilized.

A film with wide exposure latitude is needed for satisfactorily reproducing all the shades of contrast that are present in most glacier scenes. Color photography is superior to black and white in recording vegetation, which in the case of many receding glaciers is a very important change to be recorded. For this purpose 35 mm film should be satisfactory. If the photographic party is equipped with two cameras, it is believed worthwhile that the views at all the photographic stations be taken both in black and white and in color.

A desirable format for the photographic image is 4 by 5 because of its ready adaptation to ordinary 8- by 10-inch (20- by 25-cm) enlargements. With any other proportion, part of the negative must be masked when an 8 by 10 print is made; selecting the part or parts of each picture to be masked out and placing the guide marks on each negative for use of the enlarger operator is a time-consuming and relatively unrewarding process.

The rapid shutter speeds normally usable in this work make hand-held camera exposures generally satisfactory from the standpoint of negative sharpness. However, consistently better results, both as to sharpness and proper positioning and levelling of the camera, can be obtained with a tripod if enough time is available.

As mentioned earlier, no advantage has been found in this program in the use of a lens filter—such as a K-2 (yellow) one. A haze filter for reducing the effect of ultraviolet rays on film at high altitudes is helpful in color photography.

RECORDING THE PHOTOGRAPHIC DATA

When the annual photographs of Nisqually Glacier are taken, data are entered on a looseleaf "Index to Photographs" form prepared for recording the following:

Column heading	*Information indicated*
Negative No.	Serial file number, entered later in the office.
Film No.	Manufacturer's exposure number, which is given on each film of a film pack.
Cam. and F.L.	Model and size of camera, and focal length of its lens.
Film and Speed	Name of film, and its ASA speed.
By	Initials or names of each member of the party.
Date	Month, day, and year.
Station No.	Number of the photographic station.
Direction	With respect to points of the compass or to the glacier's valley, like "up" or "across".
Hor. or Vert.	Enter H or V for position in which the film is held when exposed.
Std. Time	(Inadvisable to use Daylight Time.)
Exposure 1/	For example, enter "200" to indicate 1/200th of a second.
f	Lens opening.
Filter	
Remarks	

A print of each form sheet that has been filled out with the data on a season's pictures is carried in the field for possible reference in succeeding years.

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